PEST MANAGEMENT EFFICACY AND SPRAY CHARACTERISTICS OF A SOLID SET CANOPY DELIVERY SYSTEM IN HIGH DENSITY APPLES

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ABSTRACT

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The majority of high density apple orchards are treated with axial fan radial air blast sprayers, which can result in large off target agrochemical losses since they were designed to spray larger canopies. Solid set canopy delivery systems (SSCDS) offer an alternative style of spray application, with microsprayers placed within the tree canopy for foliar applications. Limited research exists on the spray characteristics and pest management efficacy of this novel technology. My thesis research was to quantify the surface coverage, chemical deposition, and season long pest management of a SSCDS in a high density apple orchard. Coverage evaluations using water sensitive paper show that the SSCDS obtains higher levels of coverage on the adaxial leaf surface than on the abaxial surface. Additionally, SSCDS display similar levels of adaxial coverage to an air blast, but lower abaxial coverage than an air blast. Deposition evaluations with tartrazine dye show that despite the difference in coverage profiles, SSCDS treated plots showed higher levels of dye recovery, indicating more chemical was retained on leaf surfaces. Pest management evaluations in 2013, 2014, and 2016 showed little difference in levels of pest and pathogen damage in both treatments, while untreated areas displayed high levels of damage. Preliminary results suggest that both systems have similar management efficacy, while an SSCDS has the potential to offer additional benefits over air blast sprayers.

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CHAPTER ONE – REVIEW OF THE RELEVANT LITERATURE

Introduction

Improvements in horticultural practices over the last five decades have led to the steady transformation of commercial apple (Rosaceae: *Malus domestica* L.) orchards. Large, widely spaced trees have been nearly completely replaced by planar 'fruiting walls' on dwarfing rootstocks. Planting density has increased by orders of magnitude, from approximately 70-100 trees per hectare to 1000-10,000 trees per hectare, with the most common and economical planting densities at around 2500-3000 trees per hectare (Robinson, 2008; Robinson, 2013; Ferree, 2003). Despite the structural changes that define modern apple orchards, agrochemical spray-delivery technologies have remained largely unchanged. Growers still primarily rely on tractor driven air blast sprayers that were designed to apply chemicals deep into a spherical canopy with a six meter diameter (Fox et al., 2008), instead of the modern one to three meter wide linear canopies.

High Density Orchard Efficiencies

While the aforementioned transformation in orchard structure has happened over decades, the humble origins of modern fruit tree training began centuries ago in the gardens of Louis XIV of France, where the efficiency of aesthetic training was noted and then developed for the commercial European fruit industry. Dwarfing rootstocks have been around for even longer, with the French Doucin appearing in the early 1500's (Fideghelli et al., 2003). These techniques in conjunction have pushed the productivity of apples far beyond their natural limits.

Several central factors have directed the shift towards high density plantings in recent decades. Studies on the effect of light interception on apple yields have demonstrated a fundamental relationship between the two (Monteith & Moss, 1977; Wünsche & Lakso, 2000a;

Robinson & Lakso, 1991), with a highly correlated linear relationship between spur leaf light interception and yield (Wünsche & Lakso, 2000b). Canopies must receive as much available light as possible in order to optimize fruit production, and round crown trees shade their own interiors. Optimum apple harvests are achieved at approximately 60 to 70% light interception (Wünsche & Lakso, 2000a), but light levels can drop to as much as 34% of full sunlight within only a meter of the exterior of the canopy (Jackson, 1970). Therefore, as tree size decreases, shaded interior areas decrease, giving smaller trees a photosynthetic advantage and enhancing yield (Robinson et al., 2013).

Profitability has been another driving factor towards high density systems, with growers striving for early returns on orchards and finding an optimum planting density. At the beginning of an orchards productive lifespan, light interception is maximized within the smaller canopies. As such, the best way to increase yield is to increase planting density (Robinson et al., 1991). However, there is an upper limit on planting density due to the law of diminishing returns. Robinson et al. (2013) reported that, in general, around 2500-3200 trees per hectare was the optimum tree density. At a certain point, the cost of additional trees for a given orchard is greater than the overall yield, and can actually expose the grower to considerable risk if fruit prices fall and installation costs cannot be recouped.

The relatively small and accessible structure of a well-trained, high density apple orchard gives the grower another advantage. Small, flexible trees are easier to manage, and can be maintained and harvested using partial mechanization in pruning and picking. Smaller trees also require less labor to pick, as much of it can be done by hand from ground level, making them more cost effective for the grower (Daugaard, 1999; Robinson et al., 2013). These small and accessible trees, however, have completely changed the physical structure of the modern orchard, in spacing, size, and maintenance- which necessitates a close look at how crop protection materials are applied and pests are managed in the framework of this new architecture.

Common Michigan Pests of Apples & Their Management

Michigan is one of the top three apple producing states in the United States, behind only Washington and New York (USDA NASS, 2016). Washington dominates organic and conventional apple production, in part due to the semi-arid climate that gives growers an advantage over apple producers in the Midwest. Higher humidity and more frequent rainfall events during Michigan's growing season make production more reliant on chemical management than in Washington due to the increased incidence of crop damage from pests and pathogens (Granatstein, 2004; Slattery et al., 2011). Fifteen to twenty plant protectant sprays per year are common just to manage insects and diseases in temperate regions, with weekly applications from late April to mid-June (Johnson, 2004; Holb et al., 2005; Jamar et al., 2010; Wise et al., 2016).

Codling Moth and Oriental Fruit Moth are the major Lepidopteran pests of apples in Michigan, requiring a strict level of control since both go through multiple generations in a single year (Howitt, 1993). A native beetle, Plum Curculio, also requires management due to the unsightly oviposition scars and fruit damage that it causes. The most significant fungal pathogen in Michigan apples is Apple Scab, treatments in the Midwest to control primary infection are applied nearly weekly once the trees are released from dormancy, and continue well into summer for protection from secondary infection (Bordelon et al., 2017).

Tortricid Moths

The codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), is the most serious direct insect pest of apples in MI and much of the world, and if left untreated can cause crop losses of up to 90% (Epstein et al., 2008; Wise et al., 2006). The Codling Moth life cycle begins with the cocooned, overwintering late-instar larvae from the previous year. Once adults emerge, males locate females using sex pheromones (Gut et al., 2010), females then oviposit on fruit or nearby leaves. Eggs hatch in 6-14 days, and 1st instar codling moth burrow into apples, where they feed internally on flesh and seeds undergoing 5 instar before leaving the apple to pupate. In MI, 1st generation adults produce a second-generation of larvae, which cause most of the direct crop damage. The majority of this generation enter diapause emerging as adults in the subsequent spring (Epstein et al., 2008; Dowdy, 1960).

Oriental Fruit Moth, *Grapholita molesta* (Busck) (Lepidoptera: Tortricidae), is the other major tortricid pest of Michigan apples. They are a relatively recent problem, and just a few decades ago were only considered a minor pest in apple (Rothschild & Vickers, 1991). Oriental Fruit Moth have a similar phenology to Codling Moth, but, in MI, typically have three full generations rather than two. Larvae begin development at a lower temperature threshold than *Cydia Pomonella* and enter diapause later, likely the reason for the higher generation count (Chaudhry, 1956). The third generation larvae typically does the majority of the fruit damage, as they feed around harvest time when a grower’s ability to use chemical management strategies is restricted by post-harvest intervals. (Howitt, 1993)

Chemical management strategies for tortricid moth pests primarily targets their vulnerable larval stage. Because neonate larvae enter fruit within a few hours of hatching, there’s only a brief window of opportunity in which they must be exposed to chemically treated surface (Wise et al., 2010). Pheromone mediated mating disruption can be an effective tool to reduce the number of eggs laid, along with ovicides (Gut et al., 2004). Two to four sprays can be necessary to control first generation moths, while another one to two may be necessary to treat the second, for a total of three to six per season (Breth et al., 2013; Wise et al., 2010). Precise timing of sprays is critical for effective management strategies, and GDD models are used to calculate likely emergence periods.

Conventional contact poisons like organophosphates have traditionally been used for control, but regulatory measures have removed many older formulations. Populations of both moths resistant to organophosphates as well as more modern chemistries have been recorded throughout North America (Bush et al., 1993; Varela et al., 1993; Pree et al., 1998; Kanga et al., 1999; Usmani & Shearer, 2001; Whalon et al., 2012). Phosmet (Imidan) is the primary organophosphate used for control, but pyrethroids such as Asana, Warrior, and Danitol have also been widely used. Cholinesterase inhibitors like carbaryl (Sevin), insect growth regulators similar to methoxyfenozide (Intrepid) (Mota-Sanchez et al., 2008), neonicotinoids like Acetamiprid (Assail, Calypso), and spinosyn (SpinTor, Delegate) have all been used for control of both tortricid species (Wise et al., 2010). A modern, reduced risk pesticide Rynaxypyr (Altacor) is now on the market, and Granulosis virus is also an effective biopesticide (Johnson, 2004; Mota-Sanchez et al., 2008; Wise & Gut, 2015; Wise et al., 2010).

Plum Curculio

Plum Curculio, *Conotrachelus nenuphar* (Herbst) (Coleoptera: Curculionidae), is a native pest of apples in eastern North America and the northern strain, present in Michigan, are univoltine (Smith, 1957). Plum curculio overwinters as adults, emerging from diapause in the early spring. Females must feed in order for their ovaries to mature (Smith & Salkeld, 1964), and lay (on average) 73 eggs separately in young applets. Before oviposition, females chew a characteristic curved flap out of the fruit's skin that protects the larva from being crushed by the expansion of the developing tissue (Racette et al., 1992; Quaintance & Jenne, 1912). Larvae hatch out within 3-12 d (Paradis, 1956), and go through four instars while internally feeding within the apple. Larval feeding activity has been shown to induce fruit abscission at around the same time as 'June Drop', when the apple tree naturally sheds fruitlets, increasing the rate at which potential fruit are lost (Levine & Hall, 1977). Emerging larva leave the apples in which they were feeding and drop to the orchard floor, where they pupate in the soil for around a month. Adults emerge in August and feed on maturing apples, carving out cavities with the characteristic snout common to curculids (Racette et al., 1992). Damage to fruit from larval tunneling as well as punctures from the adults feeding can leaf fruit unmarketable (Wise et al., 2007).

Conventional insecticides, as with Tortricid Moths, are typically the first line of defense against Plum Curculio. Pyrethroids (Asana, Warrior) are utilized as contact poisons to control adults when they are active in the canopy, mating and feeding (Wise, 2015). Neonicotinoids (Assail, Actara) are also contact poisons, but have the additional benefit of systemic action, and have lethal effects on eggs and larvae already present in the fruit (Wise, 2013; Wise, 2015). Kaolin clay films (Surround) can be utilized as a deterrent, but requires multiple applications to build up enough of a particle layer (Wise, 2015).

Apple Scab

Apple Scab, *Venturia inaequalis* Cooke (Wint.), is a hemibiotrophic (parasite of living tissue, continues to live in dead tissue) fungus with a worldwide distribution, and is particularly severe in humid temperate climates (Bowen et al., 2010). It overwinters as in its sexual form as pseudothecia, and mating occurs in spring on contaminated leaf litter left on the orchard floor.

Male hypha fuse with female hypha and form a fertilized pseudothecium. Within the pseudothecium asci containing ascospores form, and the fungus goes through the brief diploid phase of its life forming the ascospores. Mature pseudothecia then swell and release ascospores into the environment under wet conditions and after rainfall events (Vaillancourt & Hartman, 2000). Ascospores are passively dispersed by air currents or agitation, and infect apple tissue if they land on leaves, flowers, or fruit. Secondary spores (conida) are produced at infection sites, and go on to infect additional fruit and leaves. Infections on leaves appear as darker green or brown lesions on leaves, with distinct edges. On fruit, initial infections look similar, taking on a scabby and cracked appearance as the apple matures and swells. Susceptibility is highest in young leaves and fruit, which gain more resistance as they mature (Bowen et al., 2010; Robinson & Xu, 2005)

Out of the many diseases that affect *Malus*, apple scab is the most expensive to control, requiring rigorous management (Carisse & Bernier 2002; Machardy et al., 2001). In Michigan, 75% of the agrochemical inputs from late April to mid-June are for apple scab prevention (Johnson, 2004). Treatment strategies typically focus on prevention, as secondary spore production after primary infection compounds any existing infestation. Fungicides used for control in Michigan are typically: Ethylenebisdithiocarbamates, such as Captan; Anilinopyrimidines, e.g. Vangard; and Sterol Inhibitors. Copper is an effective preventative treatment, and has a separate mode of action from traditional fungicides that inhibits resistance (Sundin, 2011).

Research Objectives

Operation of a successful spray program to manage these pests requires not only familiarity with the causal agent but the spray characteristics of the delivery system itself. The original design specifications of air blast sprayers have a number of drawbacks when applying plant protectants to modern orchards: problems with drift are exacerbated by relatively thin canopies and powerful fans; tighter row spacing forces operators to drive longer distances while covering the same acreage; and factors that impact crop health, such as disease and insects, can't be treated quickly due to the size of areas requiring applications as well as limitations on sprayer availability and passable ground. High levels of disease and insect pressures linked to the rain and humid growing conditions in the Midwest necessitate rapid responses to contain outbreaks, and it can be difficult or impossible to maneuver a sprayer in muddy orchards (Wise et al., 2017). Growing consumer concern toward pesticide residue and the environmental impacts of agrochemical runoff has also led to the inexorable replacement of broad spectrum, persistent plant protectants (such as Guthion and Methyl Parathion) with conventional reduced risk or biopesticides with shorter residuals (Wheeler, 2002; Slattery et al., 2011). Consequently, there is a need to develop an alternative to the traditional methods of agrochemical input.

My thesis presents the development and proof of concept of solid set canopy delivery systems (SSCDS) for high density apples. In SSCDS, foliar applications are delivered through a network of pressurized tubing that supply an array of fixed position microsprayers, distributed throughout the orchard canopy. This spray method provides the user with a precise tool for timing and delivering crop protection materials proactively or in response to critical periods of pest pressure and disease. Most importantly, an optimized solid set system offers the potential for superior spray coverage to current chemical input technology for high density apples.

Increasing pressure on growers to reduce the amount of chemicals on food, and the need to use less environmentally damaging methods of applying chemicals has recently prompted more research into spraying technology and its current limitations. My thesis is primarily concerned with quantifying spray efficacy provided by a prototype SSCDS within high density apple canopies. Coverage, deposition, pest management, and the system's ability to deliver foliar agrochemicals throughout the canopy must be studied in order to understand this.

History and Current Techniques of Foliar Chemical Application

Sprayers

During the late 1800s and early 1900s, technological advances in mechanical technology including internal combustion engines and pressure regulators led to the mechanization of pesticide delivery systems (Fox et al., 2008). High pressure 'spray guns' were introduced in 1914 by the Friend Sprayer Company to apply foliar chemicals, and since then, application equipment has transformed modern agriculture. The progress in building machines for applying agrochemicals has tracked closely with the increased use of plant protectants over the last century. In tree fruit, spray technology began with pressurized handguns and developed into, air blast sprayers which take on myriad forms. Most current sprayer technologies, however, share three common features: A chemical tank, a pump or pressurizer, and a set of nozzles. Since their inception, the trend in liquid spray has been to bigger pumps, larger capacities, and higher pressures (Brann, 1956).

The original style of high volume spraying with a hand gun relied on a dilute mixture of pesticide being applied by an operator until the tree had been fully saturated and chemical was running off the leaves. To spray until the point of runoff has the disadvantage of using excessive amounts of water, up to 3740 L/ha, and much of the time spent in spraying an orchard was in transportation and filling (Wilson, 1983). The benefits of individual attention to each tree were outweighed by labor and chemical costs, and hand gun sprayers were swiftly replaced by air blast sprayers.

Air Assisted Ground Sprayers

The first large dilute air assisted ground sprayer (hereafter refered to as ‘air blast sprayer’ or ‘air blast’) was introduced by G. W. Daugherty in Florida citrus in 1937 (Fox et al., 2008). Rapid adoption was favored due to labor shortages during and after WWII, and the subsequent development of highly effective and persistent chemical protectants only reinforced the trend (Fox et al., 2008). Naturally, once an effective dilute air blast sprayer design had been established, the concept was adapted to deliver more concentrated chemical formulations. Concentrates offered a major advantage over dilute sprayers: the ability to rapidly cover larger areas with less time spent filling the tank; lower labor, time, and equipment costs; and better coverage than aircraft and ground dusters. Since spray airflow projects droplets into the canopy, high spray volumes were no longer necessary to cover the tree to the point of runoff (Potts, 1958). Air blasts have advanced and diversified over the decades, but despite their reported drawbacks, it is indisputable that fruit growers have managed to attain adequate pest management using them.

Daugherty’s sprayer provided the template for most modern air blast style equipment today- a large fan pushes air at the sprayer housing, where it is redirected perpendicularly and exits through a constriction, using the narrow gap to produce a radially directed air jet. Nozzles around the circumference inject spray droplets into the airstream, and the sprayer delivers a turbulent cloud of air and chemical at 150-240 kilometers per hour (Brann, 1956; Matthews, 2014).

Modern air blast spray technology has become more sophisticated since the inception of the first crude fan powered, air assisted spray (Matthews et al., 2014). Propeller fans, centrifugal fans, and cross-flow fans have also been utilized to provide an air carrier, but the axial fan style remains the most common apple orchard sprayer types (McArtney & Obermiller, 2008). In a parallel to fan type diversification, sprayers with different air jet profiles have also been designed in an effort to produce a more effective sprayer with a more uniform distribution (Fox et al., 1998). Some modifications of air blast sprayers include: tower sprayers, cross flow fan sprayers, and over the row sprayers (Landers, 2002).

One of these adaptations is the tower sprayer, where part of the air flow pushed by the axial fan is redirected to a vertical duct that redistributes air to outlets at several heights. At each elevation the air is directed horizontally into the canopy, reducing the distance from the nozzles to the tree. This forces the air-spray mix laterally into the canopy rather than the oblique angle that typical nozzles arrangements around the circumference of an axial fan provide. The top fan outlet can be directed at shallow downward angle to form an air barrier that reduces drift above the canopy, with very few droplets projected upwards (Panneton et al., 2005).

The same premise of vertical air distribution has also been tested with cross flow fan sprayers. Several fans are arranged vertically, with the aim to provide more uniform coverage velocity, and thereby a more uniform spray (Van Ee & Ledebuhr, 1998; Fox et al., 1998). Multiple field tests by Van Ee and associates in the late 1980's reported more uniform deposition from a crossflow fan sprayer that Van Ee had been involved in the development of (Van Ee et al., 1985; Van Eee & Ledebuhr, 1988). However, a study at the Citrus Research and Education Center in Florida showed a tested crossflow sprayer had lower mean deposition of copper, and a similar coefficient of variability (uniformity) when compared to a conventional axial fan air blast (Whitney & Salyani, 1991).

Over-the-row (OTR) sprayers are a broad subcategory of sprayers. The principles behind these systems vary, but all incorporate a horizontal frame that runs over the row above the tree height, with one to several vertical gantries that hold nozzles and/or fans. Some vertical boom sprayers omit fans and air assistance altogether, a gantry holds numerous nozzles that deliver a spray that relies on high pressure for movement and atomization.

Tunnel sprayers, as the name implies, form a three sided tunnel around the tree row, with both sides and the top of the tree enclosed by a mobile framework. Directed or crossflow fans then create a turbulent air flow from both sides of the row that helps suspend spray droplets for deposition in the canopy. This design also affords the ability to integrate spray recapture equipment into the apparatus (Tennes, 1977), with spray that passes through the canopy collected and reused for even more efficiency. Chemical loss has been reportedly been reduced by up to 30% by some researchers (Cross and Berrie 1995). Tunnel sprayers are intended to reduce runoff and drift due to the enclosed nature of the machine and droplet capture mechanisms (Thériault et al., 2001), up to 95% of drift was reduced past the last downwind tree row in one study (Wenneker and Van de Zande, 2008). Results from other vineyard and orchard trials show they can achieve comparable to better levels of coverage than conventional applicators (Pergher et al., 2013; Peterson and Hogmire, 1995). However, recirculation of spray material as well as repeated contact between the frame and trees poses a risk of pathogen transmission (Fox et al., 2008).

Vertical air sleeve sprayers are an adaption of popular horizontal air sleeve sprayers used in row crops, where large flexible sleeves attached to the gantry are inflated by fans. Air passes through a slit in this sleeve, carrying droplets from nozzles situated along the periphery. Like tunnel sprayers, they can be outfitted with droplet capture mechanisms to enhance their efficiency and minimize drifts. Air sleeve sprayers have been developed and described in a number of configurations (Panneton et al., 2001; Zur, 1995; Munckhof [website]).

There are a variety of fan, nozzle, and gantry combinations that exist to provide multi-row or OTR spraying solutions, with varying degrees of success. One of the main drawbacks with any OTR sprayers is that their unwieldly shape often necessitates a skilled operator, even terrain, and a great deal of room for maneuvering around the orchard (Fox et al., 2008; Fox et al., 1998). Mechanical constraints on the both the height and width of crops tunnel and other OTR sprayers can treat, along with the inconsistency in plant size and architecture, have limited their use in America (Thériault et al., 2001).

Supplemental Technologies

Electrostatic Technology

The 1980's saw the origin and introduction of electrostatic charging devices for orchard sprayers. For large 'coarse' droplets, gravity and air velocity are the primary force acting on the trajectory and dispersion of the droplet cloud, but for finer droplet sizes (less than several hundred µm), deposition can be significantly improved with the addition of an electrostatic charge (Law, 2001). Several methods to impart the charge exist, ranging from electrohydrodynamic devices which rely on mechanical stress to electrodes embedded in nozzle tips. A two to 8 fold increase in target deposition has been reported by various researchers (Kabashima et al., 1995; Law & Lane, 2001; Franz et al., 1987; Law, 2001; Kang et al., 2004), as well as a 50% reduction in the active ingredient needed to treat a crop (Herzog et al., 1983).

Additionally, a 'wrap-around' phenomenon has also been observed; charged droplets can overshoot a surface, but the electrostatic force is sufficient to pull the droplet back onto the other side, an especially useful property when applying chemicals to leaf surfaces. The attractive electrostatic effect is highly dependent on distance to target, since up to 80% of the charge is lost to gaseous discharge as the droplet travels through the air (Law, 2001; Fox et al., 1998).

Controlled Droplet Applicator Devices

Controlled droplet applicator (CDA) technology was introduced in the 1970's, in response to the problems caused by the irregular droplet spectra caused by hydraulic nozzles. Fine droplets are prone to drift, and coarse droplets give poor coverage and are prone to run-off. Instead of relying on hydraulic pressure to form the droplets as they exit a constricted aperture, CDA's inject the spray solution onto the surface of a spinning cup or disc. The liquid travels to the outer edge and is flung from the rim, which can feature a serrated edge to further regulate droplet size. Centrifugal force broadcasts droplets that typically fall within a relatively narrow spectra when compared to hydraulic nozzles. Controlled droplet applicators can be coupled with air assist mechanisms to help move droplets through a canopy, or rely on the flinging action of the disc alone. Proptec© sprayers are a popular rotary atomizer that couple a CDA disc with a fan to push droplets within a turbulent air flow. (Combellack & Harris, 1978; Proptec [website])

Disadvantages of Conventional Sprayers

Although air blast sprayers have become the most commonly used approach for applying agrochemicals in tree fruit crops, the technology poses a number of disadvantages. Operation of an air blast carries an inherent risk of exposure to agrochemicals for the operator, both from surface contacts and aerosolized spray. Fossil fuel use and carbon debt from the operation of machinery as well as manufacturing processes contribute towards greenhouse gas emissions, and operation of heavy machinery can physically damage soil structure and plants within the orchard. The most significant problems with air blast sprayers are drift and coverage issues (Steiner, 1969; Landers, 2011). Expensive agrochemicals are wasted in poorly targeted sprays, leading to drift and toxic accumulations in the soil and water. Air blasts leave variable deposits within different portions of the canopy, and are often not properly calibrated for the orchard they are spraying.

Agrochemical Exposure

Agrochemical application in orchards using air assisted sprays provides multiple avenues of pesticide exposure. Removing the operator from the target area receiving the chemical spray would cut down exposure risk significantly, as well as reducing the amount of agrochemical residues deposited on machinery that can be a secondary source of exposure. Agricultural workers come into constant contact with a variety of hazardous chemicals, and a large body of evidence shows that there are negative short and long term health issues associate with this exposure (Quandt, 1998; Hall et al., 2002). Pesticides have long been linked with increased incidences of certain cancers in agricultural workers due to the carcinogenic properties displayed in bioassays (Blair & Zahm, 1995). Exposure from sources such as drift, residue from tools and equipment, and soils can accrue effects which may not be immediately evident to the worker, but long term, low level contact may result in subtle or delayed damage and even death (Quandt, 1998; Durham & Wolfe, 1962).

Tests by Hall et al. found that properly maintained and installed cabs were 99% efficient at removing aerosols and particles larger than 3.0μm in diameter, but included that the distribution of particles produced by the sprayer they measured included an appreciable mass of aerosol less than 3µm in size. They noted that evaporative forces and other environmental and mechanistic influences inevitably produce particles smaller than the 3µm size (Hall et al., 2002). Cavallo conducted a similar study published in 2010, and during the investigation found that an improperly assembled filter housing became a major source of hazardous material that infiltrated the cab. The study noted that the most dangerous leak sites would be around the filter that allow chemicals to bypass the filtration system and get pulled into the cab under negative pressure from filter fans. Tractor cabs can never truly be fully airtight, especially after years of repeated use in the field and the accumulated wear on seals. Positive pressure inside the cab is intended to help prevent contamination, but electrical and mechanical connections, imperfections in seals and gaskets, and defects in weld sites can all leak air or admit aerosols. (Cavallo, 2010)

Fossil Fuel Use

Agricultural activities accounted for 8.4% of the total United States greenhouse gas emissions (Lal, 2004). While much of this is from processes unrelated to tree fruit production, the number is an important reminder of how significant agriculture is to overall carbon production. Primary carbon sources are from mobile operations such as harvesting, spraying, and transporting crops; or stationary operations such as pumping water. Secondary contributions to carbon emission come from manufacturing, packaging, and other related processes. Tertiary sources include acquisition and production of pesticides, raw materials, and building fabrication (Lal, 2004).

An on farm analysis of energy expenditure and carbon production from and related to farm activities in New Zealand found that contribution of pesticide production was 10-20% of total energy consumption in high input systems (Canals et al., 2006). New Zealand has a similar wet, temperate growing environment to Michigan, which necessitates frequent applications of plant protectants. Reductions in the amount of pesticides applied could lead to significant decreases in overall energy consumption. Pesticides use is increasing globally, and even more rapidly in emerging economies. The use and production of these chemicals can be carbon intensive, and optimizing their delivery cuts down on the overall carbon load (Lal, 2004). Enhancing efficiency in on farm machinery use and pesticide applications would have a meaningful impact on the total agricultural carbon emissions.

Drive Row Compaction

Since the 1950's, changes in agricultural machinery have trended towards larger sizes and capacities, giving rise to large and consequently weighty sprayers (Brann, 1956; Håkansson et al., 1988). As vehicles move through the orchard, they can do direct damage to plants, but an often overlooked result of their repeated passage is soil compaction. Compaction is defined as the soil's reaction to external forces, leading to an increase in density. This process can negatively influence important physical, chemical, and biological properties of the soil (Becerra et al., 2010). In an agricultural setting, damage to roots and constrained growth from the passage of machinery is likely to be the most important and common concern related to soil compaction (Ferree et al., 2004).

In Michigan, this is especially significant, as most of the southern peninsula contains clay rich soils and experiences high levels of rainfall during the growing season (Andresen et al., 2012). Unfortunately, as orchards begin to develop through key phenological stages early in the year, plant protectants and growth regulators are frequently applied. Plant reactions tend to be more negative the higher the clay content, and soil strength decreases as moisture content increases. These two properties combined lead to compaction, smearing, and rutting in the spring when a large portion of the annual orchard traffic is required to achieve an optimum marketable yield later in the season. Any technology to alleviate or halt the effects of compaction from constant traffic would be beneficial to the long term health of the orchard and its soil. (Håkansson et al., 1988)

Spray Drift Causes/Mitigation

Considerable amounts of research have been done on the complex interplay between canopy and air jet as well as efforts to model theoretical deposition patterns: Salyani et al., 2013; Cross et al., 2001a; Cross et al., 2001b; Cross et al, 2003; Murray et al, 2000; Pergher & Gubiani, 1995; Walklate et al, 2002; Holownicki et al., 2000; just to mention a few. The amount of spray transported in the air jet is proportional to the air power, (Fleming, 1962) with high velocity, low volume air masses transporting droplets further than low velocity, high volume air fronts. In addition, the distance an air mass can drive a cloud of finely aerosolized particles is directly related to particle mass. A study by Pergher and Gubiani in hedgerow vineyards found that increasing the spray application rate and air jet volume led to more off target ground deposits and less foliar deposits (Pergher & Gubiani, 1995). When a high velocity air mass is produced in conjunction with small droplets, a considerable amount of off target loss occurs as the spray overshoots the target and is caught by the wind. Brann notes in his 1956 paper "an air blast is inherently a poor carrier for liquid droplets", as particles that aren't lost to drift tend to quickly lose their velocity and settle onto the closest surface. Because of this issue, air driven sprayers have a propensity to overspray the bottom levels or the tree, or the nearest branches. Large droplets simply don't have the energy to make it higher into the canopy, and it is necessary to aim five times the amount of spray at the top of the tree to obtain similar coverage to the bottom branches, increasing the risk of drift. (Brann, 1956)

Spray drift can be defined as the quantity of pesticide that is deflected from the treated area by climactic conditions during the application process (Gil & Sinfort, 2005.). This process can occur with droplets, vapors, or solid particulate that the spray consists of. The largest contributing factor to this process is the speed and direction of any wind (Miller, 1993 [excerpt from Matthews et al., 2014]), as the likelihood of drift has a linear relationship the wind speed over the course of the application. Small droplets or particles are the most likely to be carried by ambient air flow, so possibility of drift is correlated to the proportion of the spray volume that is under a critical threshold size defined by the size at which the droplet may be carried by the current wind speed. Between 30-50% of the application can be lost to drift, and even pesticides that have been applied to orchard surfaces may be released to the atmosphere by volatilization (Matthews et al., 2014). Research studying drift from the common axial fan air blasts has demonstrated losses of over 50% of the spray material (Steiner, 1969; Herrington et al., 1981; Cross, 1991; Doruchowski et al., 1997). Pathways such as hydrolysis, photolysis, and wind erosion may break down and spread agrochemicals or the products of their degradation away from the target site (Ebeling, 1963).

While spray drift is an omnipresent factor that can never be fully controlled without enclosing the treated area, several contributing factors can be controlled. Drift mitigation relies on understanding the interplay between mode of application, droplet size, nozzle types, formulation adjuvants, wind direction, wind speed, air stability, relative humidity, temperature, and height of spray relative to crop canopy (Felsot et al., 2010). Field layout and orchard architecture are important, because cross winds are baffled and redirected by the porous and semi porous boundaries of the tree row. Buffer zones and windbreak crops are common practical drift mitigation practices around the treated area. It is important to remember that despite the negative impact off-site drift can cause air and particle movement within the treated area is important for even coverage, and increases the active ingredient deposits on foliage (Felsot et al., 2010).

Variable Coverage / Not Optimized for High Density Apples

Every year, hundreds of metric tons of agrochemicals are applied to crops in the United States. In apples alone, 7.28 million pounds of active ingredient were applied to protect 2008's crop (Fernandez-Cornejo et al., 2014). Despite the enormous quantity of pesticides applied to this crop, only .1% of the chemical is intercepted by its intended recipient (Graham-Bryce, 1977; Pimentel, 1995). The remainder either degrades in situ or contaminates the environment, moving through water, soil, and the atmosphere. Wind currents may transport small pesticide droplets or chemicals in their vapor phase long distances (Pimentel, 1995). The intensive use of pesticides in modern apple production necessitates precision when applying chemicals in order to reduce expenses, maximize effect, and minimize environmental exposure to toxic and persistent compounds.

The tried and true standby of most orchard spraying is the radial airflow axial fan air blast sprayer, widely used because of its simple design and relatively low price. These sprayers, however, produce a turbulent cloud of particles that is not suited to the architecture of modern high density production (Holownicki et al., 2000). Greater deposits within the canopy are achieved with higher air velocities, but this has the unintended effect of increasing emissions to the air. Holownicki found that deposits from a conventional axial fan sprayer were significantly lower than those achieved with other sprayer arrangements, except in cases where the conventional sprayer was used in narrow row spacing. Additionally, many of the spray nozzles used for applications in orchards were originally developed for row crops, which have an entirely different profile and spray orientation (Jones et al., 1999). Using equipment originally designed to apply chemicals down onto a flat profile rather than the vertical, complex canopies of trees has proved to be challenging and results in variable coverage.

Herrington took an in-depth look at quantifying spray coverage on the various components of apple trees. Their experiment with a copper tracer found that at full foliage, ‘hedgerow’ style trees only retained 63% of the spray volume using the typical low volume spraying (560 L ha-1) and only 25% of the spray volume with ultra-low volume spraying (45 L ha-1) (Herrington et al., 1981). As expected, the amount of spray deposit on the various components (trunk, branches, leaves) of the tree was proportional to the surface area of each component. Another study in 1985 found very similar results, 65% of spray from a standard air blast deposited within the targeted trees, but 35% was lost to drift and the ground (Byers et al., 1985).

Poorly optimized spray coverage is also evident levels of deposits found within experimental target trees. Radial airflow sprayers overspray the bottom levels of the canopy, while underspraying the top portion (Brann, 1956). Sprayer nozzles should be configured based on the principle that the specific crop geometry and canopy architecture of the orchard in question are more important than general guidelines (Giles et al., 1989). However, agrochemical product labels typically lack specific directions on tailoring application rate and sprayer configuration to suit the many different orchard architectures that are treated with axial fan sprayers. The air flow volume is usually adjusted to effectively spray the densest canopy conditions and left as-is when spraying trees with a lower canopy density. This, along with the fact that many times a variety of crop structures are treated with sprays using one type of sprayer and configuration exacerbates the problems with the typical conventional air blast sprayer’s coverage (Walklate et al., 2002).

History and Challenges of the SSCDS Concept

The concepts underlying a solid set canopy delivery system are, in many regards, similar to that of any other spray system. Spray material from a prepared tank mix is pumped through nozzles where it is broken up into discrete droplets and applied to a foliar surface. However, in a SSCDS application these various components are distributed and controlled from a single location, rather than the mobile platform of an air blast sprayer. The current iteration of this system utilizes a series of microsprinklers (or microemitters, used interchangeably in this text) distributed throughout the orchard, positioned within the linear wall of the canopy. These emitters are attached to and fed by lateral lines- pipes suspended from the trellis system common to high density orchards. Piping runs down the length of the treated row, and then loops back to the 'front' of the orchard, where the individual lateral lines from each tree row attach to two main lines- one that supplies pipes going up into the canopy, the other for the return end of the loop. These main lines terminate at a manifold, where the operator can control applications. The major powered components of the system are linked to the manifold: a reservoir tank containing the spray material, a pump (or series of pumps) that fill the system with liquid and pressurize it for application, and an air compressor that clears excess fluid from the lines and returns it back to the reservoir once an application is complete. The volume of spray applied can be modified through either changing the duration of application, pressure of the spray, or a combination of the two.

Variations of this concept have existed for decades, and in recent years a confluence of events have made the system feasible. Mass manufactured microemitters, more durable materials, high density orchards, and a recognition of the need for more precise chemical delivery strategy have all pushed the development and recognition of this concept.

Early Research into SSCDS

Microsprinklers were prevalent in orchards prior to any chemigation efforts, citrus and avocado producers in California and Florida utilized in-canopy and ground based sprinklers to provide frost and freeze protection in spring. Water can provide cold protection to crops when properly applied, but may also ice trees or increase chilling effects if done improperly. The heat of fusion when water freezes to ice releases 1200 BTU per gallon, and can keep ambient temperatures around or above 0˚C with constant application. (Parsons & Boman, 2003; Buchanan et al., 1982; Bourgeois et al., 1990) This prevents new growth or vulnerable tissue from sub-zero temperatures, but must be carefully maintained. Integration of microsprinklers into orchards for multiple uses was then a natural progression from these ideas.

The first investigations into using overhead sprinkler systems for chemigation of tree fruit as well as irrigation began in the mid 60’s at the Southern Oregon Experiment Station. At the time, overhead sprinklers for orchard irrigation were not a new concept, but Porter Lombard posited that a modification of the existing system would yield a multi-purpose tool. Their aims were twofold, to test whether it would possible to use contemporary irrigation technology to provide frost protection and summer pest control. Two unreplicated nine acre plots of Bartlett and Anjou pears were prepared, and 1/8” Rainbird 14V TNT sprinkler heads were installed every 50’(every other tree) on 20’ risers. Test plots were compared to identical ‘check’ plots which were treated with the same material by speed sprayer at the same rate per acre. Due to the technical limitations of their system, and the novelty of the idea, pest control in the overhead sprinkler plots was inadequate, and had poor control of pear psylla, *Cacopsylla pyricola* (Förster) (Homoptera: Psyllidae); two-spotted mite, *Tetranychus urticae* (Koch)(Acari: Tetranychidae); and codling moth *Cydia Pomonella* with Guthion applications. Lombard noted that sprinklers deposited far less pesticides when compared to the air blast sprayer because the mechanics of their system forced them to apply three minutes of pesticide slurry and then eight minutes of water, which likely washed off much of the active ingredients. His closing remarks noted that improvements to the system would possibly make it a competitive alternative to other treatment methods. (Lombard et al., 1966)

The next forays into using microsprinklers for chemical applications mainly focused on design parameters and economics rather than constructing and testing a system. Several important features of a fixed spray system were identified, many of them borrowed from research into microemitter cooling in citrus crops, as well as the already common center pivot and solid set systems in row crops. An anti-siphon check valve to prevent agrochemicals from draining backwards through the system to the water source was an imperative safety device mentioned to prevent contamination. Positive shut off valves on chemical source tanks and a check valve on the chemical feed line to prevent irrigation water from overflowing the supply tank were also deemed necessary (Sawyer & Oswalt, 1983; Wilson, 1983; Carpenter et al., 1985; Threadgill, 1985). Also stressed was the importance of corrosion resistant valves, lines, and injection equipment, as chemigation systems could be dangerous to the orchard and operator if the wrong materials were used in both construction and injections.

Another consideration for an effective solid set system is calibration. Sawyer and Oswalt note that, “The application of crop protection chemicals through MS(microsprinkler) systems will only be as accurate as the system design permits.” Uneven applications must be avoided through proper design, and calibrations made to determine uniformity. Homogeneity of chemical distribution is an essential aspect of any chemical delivery system (Threadgill, 1985). Each emitter must release an equal volume of liquid for the duration of the spray event. Wilson’s master's thesis notes that according to the ASAE's Engineering Practice EP367.1 (Agricultural Engineers Handbook; 1982) the flow rate for each nozzle head shouldn't differ by more than 5%. Therefore pressure may not vary by more than 10% along the length of the line, because the change in flow rate is proportional to the square root of the change in pressure (Wilson, 1983). Under dosage and over dosage both carry their own risks, such as pest survival and resistance or phytotoxicity to the plant.

Wind velocity is a critical environmental factor affecting emitter droplet dispersion- it can distort water application pattern causing unequal distribution. Older studies posit that low pressure and large droplet sizes are needed to combat drift from the sprayers, primarily because designs at the time featured a single sprinkler set above or between canopies, rather than within the foliage (Carpenter et al., 1985). A method of determining the coefficient of uniformity was also reported by Sawyer and Oswalt, to counter perceived application problems. However, modern stop-drip diaphragm technology renders this type of calibration unnecessary since the line is evenly pressurized, and sprinklers are prevented from spraying until a certain critical pressure threshold is exceeded. Their hypothetical system had to be filled and run until all sprayers were emitting fluid, and balanced at full operational pressure (Sawyer & Oswalt, 1983).

The primary design of the time was planned around semi-dwarf apple trees with 5.5 m diameter canopies. An underground network of pipes was planned, to supply a pesticide and water treatment to a sprinkler on the top of each tree. A main feed pipe ran perpendicular to tree rows through the orchard, bisecting it into two halves. Perpendicular lateral lines would branch off from the main pipe and run between the tree rows, buried underneath the drive row which was conserved for accessibility. Sets of four junction lines would then be connected to the lateral lines, and run up to feed the sprinkler positioned above each tree canopy. Lateral spray could be controlled from an electronic solenoid valve connected to a microcontroller (Carpenter et al., 1985). While this system was never constructed, various separate commercially available components were tested and modified. Pipe configurations and resulting pressure requirements were determined, along with suitable microsprinkler styles.

After identifying suitable materials, economic models were then constructed based on the components deemed optimal for use. Carpenter and Wilson ran cost analysis on based on materials for a 1, 4, and 10 hectare orchard size over the projected 30 year life of a standard orchard. Materials and costs at the time indicated systems were only economical for an orchard 6.5 ha or less when compared to an air blast sprayer. While these figures are nearly four decades old, it is an important point that economics of the system vary with size of orchard. However, this model didn’t take into account alternative services provided by a permanent spray system. (Carpenter et al., 1985)

Each of these early studies immediately noted and reiterated the apparent advantages of a SSCDS that hold true today. A fully functioning fixed spray system for tree fruit would offer a diverse set of advantages: Reduced application time, reduced labor and energy costs, reduced equipment needs, greater timeliness and precision of sprays, as well as reduced operational hazard. On the other hand, these studies also cautioned that there were potential disadvantages, as a system would require specialized equipment, and in the form they envisioned it, may require excessive amounts of water due to the spraying constraints and styles of the time.

Modern Research

In 1998 Art Agnello revisited the fixed spray system concept, this time in high density, dwarfing rootstock apples apples. At Cornell’s Geneva experiment station they built a system closely resembling the original concept designed by Carpenter and Wilson. However, the new project opted to run lateral lines above ground on poles at three heights, rather than below the orchard floor. Greenhouse style micro-emitters (Netafim DAN 7000) with a flat spreader and a .8 mm orifice were plugged into the line every six feet. The fixed line system was compared with a conventional air blast sprayer in terms of disease and pest management for the two years of operation, 1998 to 1999. It showed comparable suppression, and encouraged further research. (Agnello, 2007)

In 2005 a larger scale system was assembled, based off of the 1998 version and its success. Counter to previously held ideas in the 60's to the 80's, small droplet sizes were desired, as research has shown small droplet sizes provide excellent coverage (Bode, 1981; Hodgson, 1990). An aerometrics PDPA 1-D laser system was used to select the emitter with the finest spray. The same emitters were utilized on the same spacing, but construction was scaled up to a .9 acre block of dwarf super-spindle Gala apples. Lateral feed lines were affixed to the trellis wire in the first example of an SSCDS utilizing the existing structures necessary for high density apple production. A direct injection system was incorporated into the design, but testing with tracer dye later revealed an unacceptable delay in the time it took to reach the furthest nozzles. Because of this deficiency, direct injection was halted. Instead chemicals and water were combined directly in the mix tank and pumped through the system.

While the modifications for direct injections were not successful, other incorporations based on the original design parameters were installed, namely 10psi check valves on each emitter. The same insecticide and fungicide regime was applied to two halves of the orchard in July and August 2006, with one side treated with an air blast, and one side treated with the new SSCDS. They observed equivalent insect and disease control in both plots, with no significant differences in foliar terminal or fruit damage attributable to the treated time frame. In 2007 they repeated their experiment, this time with the full season of scheduled insecticides, fungicides, thinners, and foliar nutrients applied through the system. Again, no significant differences were observed in foliar terminal insect damage, fruit insect or disease damage, or fruit load. In season sampling revealed near zero damage in both air blast and fixed spray blocks, while late season evaluations showed that both halves produced 96-97% clean fruit (Agnello & Landers, 2006; Agnello, 2007).

Research at Washington State University (WSU) in conjunction with Michigan State University (MSU) and Cornell University concentrated on testing appropriate materials for the construction of a commercial sized spraying system. Sharda et al. compared the fluid dynamics of two potential hose materials- rigid polyvinyl chloride (PVC) and flexible polyethylene hose. Pressure transducers were mounted within the system to collect data on flow rates, pressure drops along the length of the system, and time delay until pressure stabilization within the system. Time delays for PVC hose systems were lower, meaning the system approached pressure stabilization faster. Both systems exhibited similar pressure drops along the length of the tested segments. Additionally, PVC resisted the torsion that flexible PE hose undergoes under spray conditions (rotating around its axis) which helps keep nozzles in alignment. The authors noted that the cost of PE and PVC hose was similar (about $0.32/meter), and these properties suggest a PVC (or similar material) hose system would be superior to a flexible hose system (Sharda et al., 2013).

Subsequent research at WSU was then focused on optimizing emitter style and configuration, to determine which commercially available microemitters seemed to give the best coverage. Water sensitive spray cards were set up in 22-25 random locations within three trees in the upper, medium, and lower regions as well as varying distances from the trunk. Sprays were applied to each of the six emitter types and four configurations, and then cards were collected and digitized for analysis. Observations showed that the previously held standard of a single emitter above each canopy actually provided the least effective coverage, since much of the spray was immediately occluded by foliage and didn't penetrate the canopy well. Alternate configurations revealed that it was important to locate sprinklers lower in the canopy oriented so that spray is directed upwards, rather than immediately above the tree. Configurations that only distributed spray down onto the surface of leaves quickly spread out and trickled downwards without treating the underside of the leaves (Sharda et al., 2015).

Parallel studies at WSU explored the potential of an SSCDS to treat cherries trained to upright fruiting offshoot architecture, as well as apples trained to tall spindle. The installation of the SSCDS in research plots also allowed researchers to look at coverage as well as some ancillary benefits of the system; sunburn prevention through evaporative cooling in apples, and the application of plant growth regulators in cherries (Hanrahan et al., 2014; Niemann & Whiting, 2014).

Plant growth regulator applications showed no significant differences between air blast, SSCDS, and UTC treatments, however within-treatment variability was high (±19%). The authors suggest different nozzle placement or nozzle type may improve canopy penetration and reduce inconsistency. Sunburn reduction trials in apples had greater success, with SSCDS showing an ~50% reduction in Y2 sunburn (Schrader/McFerson Sunburn Scale) in the upper canopy of 'Gala' blocks compared to standard evaporative cooling methods and untreated control. SSCDS treatments also had significantly lower Y2 sunburn in the lower canopy as well. Two styles of water application were tested through the SSCDS, one with shorter more frequent sprays, one with longer less frequent sprays, and the authors concluded that the more rapid short pulses of cooling sprays were more effective for cooling (Hanrahan et al., 2014).

SSCDS coverage evaluations in the same orchards showed that the air blast provided better coverage overall, as well as higher deposition. In apples, coverage on air blast treated spray cards was 55% higher overall, when combining all heights, dates, and orientations. Orientation of the cards was important, the air blast gave 80% more coverage on the underside of spray card pairs, and 22% more on the upper surface. Disparities in coverage were less distinct in cherries, with no difference in coverage on the adaxial surfaces. Abaxial surface coverage was 51% higher however, and the authors attribute this to the turbulent air and droplet plume that moves leaves around and leads to higher droplet interception on the underside. SSCDS systems, they note, tend to have more of a 'droplet shower' effect. The authors noticed that droplet patterns from the air blast on spray cards were more uniform than those deposited by the SSCDS system, which had many instances of over/under spraying. Deposition is also an important measure of spray efficacy, and trials showed that the SSCDS delivered 8.7µL/cm^2 of product compared to the 39.9µL/cm^2 collected from air blast treated leaves (Niemann & Whiting, 2014).

Field experiments in Quebec testing low drift, sprinkler, and conventional nozzles in high density apples suggested perfect coverage wasn't required for effective disease and pest suppression. While each emitter type deposited different amounts of spray in different canopy areas, disease and pest suppression was relatively equivalent in each system. They speculated that pesticide efficacy simply requires appropriate coverage, rather than an absolute threshold, and is determined by pest type and ambient conditions (Panneton et al., 2011 & 2015). Research in France at CTIFL (Centre Technique Interprofessionel Des Fruits Et Legumes) corroborated the Canadian findings. Spray deposits with the SSCDS installed there were much more variable and heterogeneous than an air blast used for comparison, which according to accepted literature is inadequate (Matthews et al., 2014). However, both the air blast and SSCDS had comparable efficacy in suppressing apple scab, with no significant differences found between the two, and significantly better scab control in both treatments than in the untreated block: 3% vs. 98.5% damage (Verpont et al., 2015).

Measuring Foliar Chemical Application

Testing spray systems necessitates efficacy tests, either directly or through a reliable proxy. There are many methods of evaluating spray application technology, but they can be reduced down to two main approaches: characterizing pest and disease control, or measuring spray deposits and coverage (Holownicki et al., 2000). While biological efficacy is the endpoint that the grower is dependent upon, this style of experimentation requires far more money, time, and space than the quantitative measurements that fall in the second category. Spray deposit and coverage measurements give a researcher or grower a relative tool from which inferences about biological efficacy can be drawn. Measuring deposition and coverage rather than pest management efficacy allows the researcher to compare the efficacy of different prototype setups rapidly and multiple times over the course of a single season. They can also be used to establish how the characteristics of a particular spray system change in response to canopy expansion and growth over time.

Deposition and coverage are two closely related aspects of spray assessment. Deposition measurements are collected by determining the total quantity of a chemical retained on a surface, while coverage measures the distribution of the spray on the plant surface. Deposition is informative when determining how much chemical is applied to a surface, but doesn't distinguish how well distributed that chemical is on the leaf- whether it was one large droplet or a multitude of fine impacts. Methods for evaluating spray deposit can be chemical (active agrochemicals) or optical (fluorescent chemicals or colored dyes) that determine concentration per area. A compound is applied to a canopy, and then leaf or other vegetative samples are collected. The tracer dye or spray material is then washed off or extracted for quantification.

A common and effective measurement of deposition can be carried out through absorption spectrophotometry. When using food grade dyes, spectrophotometry is economical and presents no health hazard to the applicator. Error is also minimal for high enough concentrations, (above 1mg L^-1) and recovery variation is low on different surfaces, such as leaves or paper (Sánchez-Hermosilla et al., 2008). Tartrazine is a synthetic yellow azo dye (FD&C Yellow-5) that is water soluble, with a maximum absorbance when dissolved in water at 425 nm, within the visible spectrum (400-700 nm)(Sharp). Tartrazine is also an easily extracted dye with favorable photostability when compared to other fluorescent and food grade dyes, with low photodegradation when used outdoors and a high recovery rate due to its solubility (Pergher, 2001). These characteristics make it an excellent candidate for spray deposition assessment, where it has been used extensively. However, this alone is not enough to characterize spray efficacy. Coverage data is also required, indicating the proportion of an area that is treated. (Holownicki et al., 2000).

Coverage demonstrates the extent of the treated area, but not the amount of chemical that was actually deposited, or whether a high enough rate was applied for biological activity. Measurements of coverage are often taken with oil or water sensitive cards that change color when they come in contact with droplets. Target cards are placed at various heights and locations within the canopy to simulate artificial leaf targets, and then sprayed in a simulated application. Area covered by the spray on the card can then be obtained by dividing the triggered area by the total sample surface area. Coverage measurements not only provide an estimate of the percentage of a surface covered by spray, but also the uniformity of the spray. Spray coverage and consistency is arguably the single best predictor of whether an agrochemical delivery system will provide the desired performance.

Objectives of the Present Work

As with any spray technology, adequate and relatively uniform coverage is one of the most important factors to be considered. Little is known about the coverage efficacy of solid set canopy delivery systems at large scales and within the three dimensional structure of the foliage. Previous coverage trials were conducted on single trees, pairs of tree rows, or on small plantings; and are based upon a limited amount of data collected from few trees. In order to properly characterize the distribution of droplets throughout the canopy and the planting, sizeable square plots intended to simulate orchard wide installations need to be sampled. Additionally, there is a gap in knowledge about season long pest management efficacy of the system, with most prior studies lacking replication and conducted on a limited temporal scale that does not accurately reflect the characteristics of a full growing season. Therefore this study was designed to resolve these questions by testing the overall pest management of the prototype system and to characterize the spray coverage it provides, thereby helping growers better manage chemical inputs in high density apples. The specific objectives were:

1. To quantify spray coverage on both the upper-side and under-side of leaf surfaces at

different levels within the canopy and across the area of each plot when using an SSCDS

2. To assess how spray coverage throughout the plot and within the canopy changes during the season as the apple tree develops
3. To evaluate season long pest management of the system and its ability to suppress pest and disease pressures compared to traditional air blast sprayers by assessing tree and fruit damage throughout the season.

CHAPTER TWO – COVERAGE AND PEST MANAGEMENT OF A PROTOTYPE SOLID SET CANOPY DELIVERY SYSTEM

Introduction

Modern apple production has changed markedly in recent decades- new varieties, rootstocks, machinery, and plant protectant formulations give growers better tools to adapt to changing markets and conditions. Transformations in canopy architecture stemming from the advent of commercial dwarfing and semi-dwarfing rootstocks have reduced the stature of individual trees and increased planting densities by orders of magnitude (Robinson, 2008; Feree, 2003). These changes were largely driven by the array of benefits that high-density orchards offer – including precocious yield and a higher quality and quantity of fruits per unit area. Smaller, more flexible trees also lend themselves to partial mechanization of management and harvest more readily than thick, branched, complex canopies (Robinson et al., 2013).

While fruit tree canopies have undergone massive structural changes, the agrochemical application technology has remained largely stable since the introduction of the first radial air blasts in the mid-20th century. Air blast sprayers were designed to throw sprays into the center of large, spherical canopies rather than the shorter, linear canopies of high-density orchards (Fox et al., 2008). This application method results in a voluminous cloud of high speed, chemical droplet laden air that delivers variable coverage distribution within the canopy, and typically isn't adjusted for the row height and foliage density (Holownicki et al., 2000). Research studying drift from the common axial fan air blasts has demonstrated losses of over 50% of the spray material (Herrington et al., 1981; Cross, 1991; Doruchowski et al., 1997). Furthermore, air blast sprayers are expensive, require a skilled operator, and incur long term upkeep costs from maintenance and fuel. The weight of the tractor and full sprayer may also cause soil impaction and root damage in the drive row (Håkansson et al., 1988). Drift resulting from the atomization of chemical solutions in high speed air fronts leads to environmental pollution, and the energy inefficiency of generating aforementioned air front have also been persistent design flaws since the inception of the air blast sprayer (Carpenter et al. 1985).

Growing consumer concern about pesticide residues and the environmental impacts of agrochemical runoff has also led to the gradual replacement of broad spectrum, persistent plant protectants with conventional reduced risk chemicals and biopesticides. These compounds typically have short residual periods and are often more expensive (Wheeler, 2002; Slattery et al., 2011). In order to suppress pest and pathogen issues, growers must spray more frequently and at a higher cost per spray. Consequently, there is a need to develop an alternative to the traditional methods of pesticide and nutrient application.

A solid set canopy delivery system (SSCDS) optimized for high-density tree fruit would have the potential to counter-act many of these problems. Foliar applications would be delivered through a network of pressurized polyethylene tubing supplying an array of microsprayers distributed throughout the orchard canopy, utilizing the existing support structures and trellis wires common to high-density fruit production. The design and placement of the emitters within the canopy, and the absence of a moving air front, may help avoid one of the major drawbacks of air blast sprayers- an indiscriminate plume of spray that loses a large portion of the droplets to the ground and to drift.

Rapid application of agrochemicals simultaneously throughout an orchard would allow the user to cover a large area during key pest management timings and under soil conditions that are not conducive to moving heavy equipment through the orchard. Important Insect phenological stages include such critical periods as first flight, oviposition, and larval emergence. Thinning sprays for trees may be applied over a large portion of the season, from bloom to 25 mm fruit (Schwailler, 1996), but the timing for effective sprays is largely dictated by weather conditions (Greene, 2002). Additionally, inclement weather that is conducive to the spread and development of pathogens can only be predicted in the short term, and a rapid application would allow growers to spray crop protectants at short noticex. This may also improve the grower's ability to effectively use targeted reduced risk conventional pesticides and biopesticides, which have short residuals and can require frequent application (Lacey et al. 2007).

Other ancillary advantages of removing a tractor from spray requirements include a reduction in fossil fuel use, and decreased exposure to chemical inputs for the operator. Any reduction in drift and soil infiltration of agrochemicals lets an operator either reduce the amount sprayed or ensures that a higher portion of the chemical is retained in the foliage and is available for its intended purpose. Finally, and most importantly, an optimized solid set system offers the potential for better spray coverage than current chemical input technology for high-density apples.

Early research into solid set canopy delivery systems focused on feasibility (Lombard et al., 1966) and design specifications and operation (Sawyer & Oswalt, 1983; Wilson, 1983; Carpenter et al., 1985; Threadgill, 1985), but failed to provide pest management due to the hydraulic engineering constraints of the time. Agnello and Landers revisited the concept at the New York State Agricultural Experiment Station in the early 2000's utilizing modern greenhouse microsprayer components. Preliminary studies on pest management efficacy of the system in New York showed promise, the SSCDS installed there had equivalent insect and disease control to an air blast sprayer, with no significant differences in foliar terminal or fruit damage attributable to the treated time frame (Agnello and Landers, 2006).

Recent work has focused on preliminary coverage measurements (Lang and Wise, 2010), fluid dynamics and appropriate piping materials (Sharda et al., 2013), and emitter configuration and style (Sharda et al., 2014). The potential of the system for evaporative cooling was evaluated in Washington, where high temperatures and sunburn can damage fruit, with promising results (Niemann et al., 2016). Trials evaluating spray coverage in cherries and apples in Washington showed lower overall spray card coverage when comparing the SSCDS to the air blast, as well as more variable deposition patterns (Niemann and Whiting, 2016).

However, as with any spray technology, adequate coverage is one of the most important factors to be considered. Little is known about the coverage efficacy of solid set canopy delivery systems utilizing modern microsprayers. Coverage affects the amount of biologically active material on leaf surfaces, and bioassays assist in determining whether the system's spray profile will provide acceptable protection. More information is also required regarding the season-long pest management efficacy of the system when compared to an air blast sprayer. Therefore this study was designed to resolve these questions by directly comparing the overall pest management of the prototype system with an air blast and untreated control, as well as to characterize the spray coverage it provides at different levels within the canopy. The specific objectives of this project were:

1. Quantify spray coverage on both the upper-side (adaxial) and under-side (abaxial) of leaf surfaces at different levels within the canopy using water sensitive cards.
2. Evaluate season-long and general pest management of the system and its ability to suppress arthropod pests and plant diseases compared to traditional air blast sprayers through bioassays and damage evaluations.

Materials and Methods

Solid Set Canopy Delivery System

The canopy delivery system was comprised of upper (2.5cm) and lower (1.9cm) Blue Stripe® Poly Tubing polyethylene hoses (The Toro Company, Bloomington, Minnesota, United States). Hoses formed a continuous loop, with the 2.5cm line running the length of the orchard attached to the trellis wire with clips (NaanDanJain Irrigation Ltd., Israel) at 2.6m. Hoses then dropped down and were affixed to trellis wires at 1.2m, and line diameter decreased to 1.9cm for the return portion of the loop.

All microsprayer components were manufactured by NaanDanJain Irrigation Ltd. On the top line, single Jain Irrigation Modular Group 7000 series microsprinklers with 0.8mm aperture ‘violet’ nozzles and ‘yellow star’ static spreaders were attached to 124 kPa leakage prevention devices (LPD) and oriented vertically, spaced 1.8m apart. The lower line used two of the same emitters, attached to a ‘Tee’ bridge and stop-drip device inserted into the line, oriented horizontally and also spaced 1.8m apart. Individual components were fitted together with friction connectors that were pushed together, and attached to the line with a barbed fitting inserted into the hose. The emitters on the top and bottom lines were offset such that they fell in between the two emitters above or below them, with a microsprayer on either the top or bottom line every .9m.

The application equipment consisted of three major components; a pumping system, an air compressor, and a tank for providing and recapturing excess spray material from the system. Line pressurization and chemical delivery was provided by two tandem pumps powered by

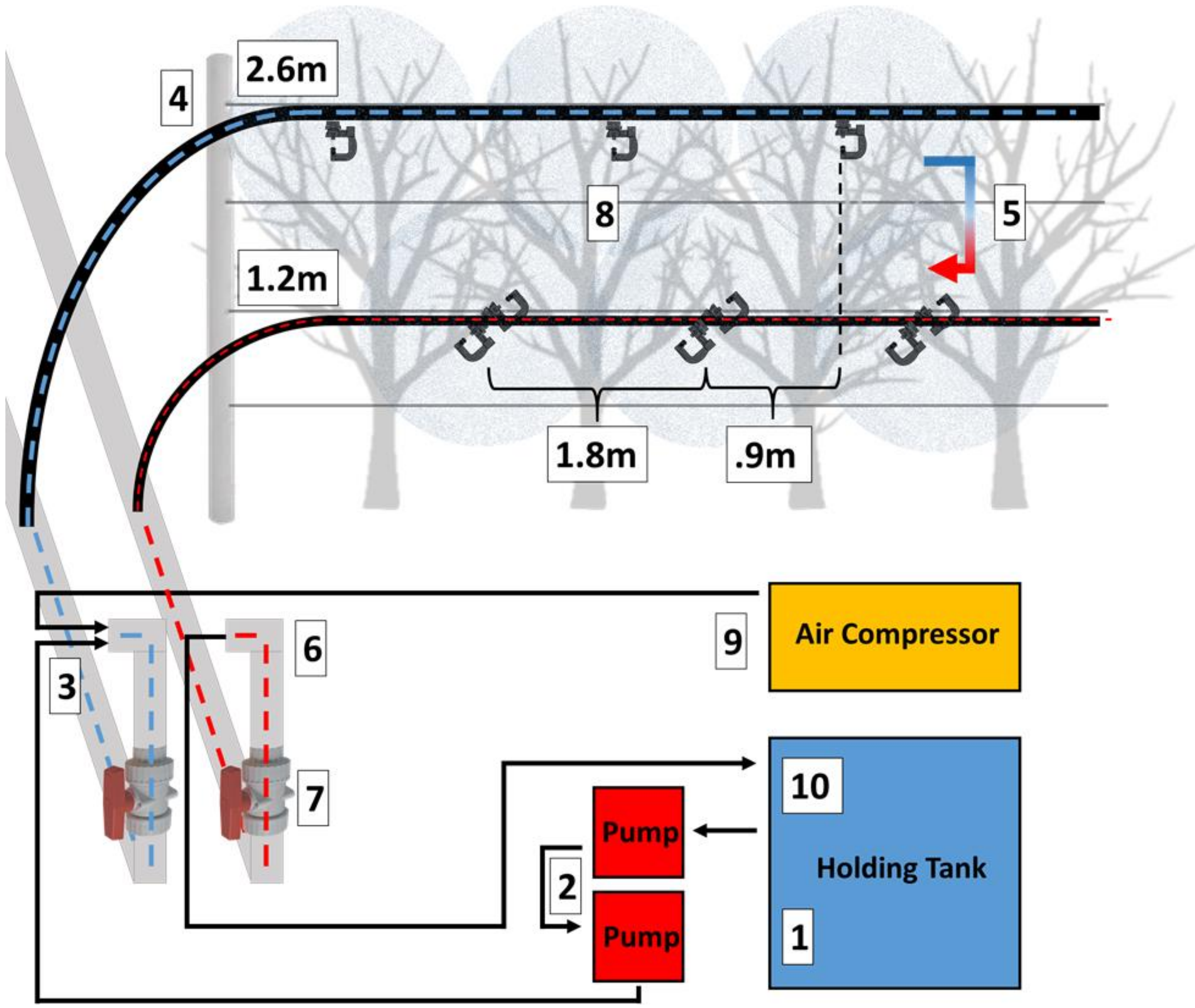


Figure 2.1 Schematic of 2013/2014 Solid Set Canopy Delivery System

1. Spray mixture in holding tank.
2. Mixture drawn from tank through tandem pumps.
3. Spray is pumped to manifold at <124 kPa, and into lateral lines, the 5cm PVC pipes underground in front of the orchard.
4. Once lateral lines are filled, liquid moves up into 2.5 cm polyethylene delivery lines.
5. Spray material fills top delivery line, and then returns along 1.9 cm bottom line.
6. Circulated liquid is returned to holding tank and lines are entirely filled with spray mixture.
7. Return valve is closed, and pumps increase pressure to 276 kPa, overcoming the 124 kPa leak prevention device.
8. Spray is applied through emitters for 12 seconds.
9. Return valve is opened, and air compressor fills line with air, pushing the excess spray material through the loop.
10. Once lines are emptied back into holding tanks, air pressure is increased to purge the remnants of spray from the lines and residues from the nozzles.

Honda GX160 160cc engines. Spray formulation were drawn from the holding tank, an FMC 350 Series PTO Orchard Sprayer, and then pumped through the manifold, along the main line, and up into lateral lines. Filling lines was completed while keeping the pumping pressure under the minimum spray pressure of the 124 kPa LPDs. Once fluid had completely filled the system and was flowing back to the tank return line ball valves were closed and the pumps throttled up to approximately 276kPa for the application. After sprays were completed, return line valves were opened and excess fluid in the lines was pneumatically purged with a hydraulically actuated air compressor (BOSS Industries 80102 AHBI) at a pressure lower than that required to overcome the LPD on each emitter (124 kPa). Fluid flowed through the output line and back into the holding tank of the air blast sprayer (Fig. 2.1). The recirculated and remaining plant protectants were then applied through the air blast sprayer to comparison plots.

Experimental Area

Experimental plots were established in a mixed variety apple orchard at Michigan State University's Clarksville Research Center (CRC), in Clarksville, Michigan. The one hectare planting consisted of three varieties: 'Crimson Royal Gala' on M.9 rootstock; 'Honeycrisp' on B.9 rootstock, and 'Rubinstar Jonagold' on B.9 rootstock. Trees were trained to the tall slender spindle system at a .9m in-row spacing and 3.35m between-row spacing. Planting density was 3720 trees ha^{-1}.

Twelve experimental units were established in the orchard: four untreated control plots, four air blast plots, and four solid set canopy delivery plots in a completely randomized design. Each plot consisted of 408 trees – 136 of each variety. Plots were twelve rows wide and 17 trees long; and were held the same throughout the study. Pest management data collection was in the middle two rows of each of the three varieties spanned by the plot. In the SSCDS plots, a microsprayer array was installed in the middle two rows of each apple variety.

Coverage Recording

Coverage was recorded and quantified using water sensitive paper (WSP) cards (TeeJet®, Spraying Systems Co., Wheaton, IL) placed throughout the canopies of eight different semidwarf Rubinstar Jonagold trees. A single tree from each of the four SSCDS and four air blast plots was selected. Cards were cut to 26×26mm in 2013 and 2014. Each WSP had a white mailing label (Avery®, Brea, CA) fixed to the reverse side recording treatment, replicate, tree location, date, and orientation. Cards were placed on both sides of the tree respective to the row at three different vertical locations: 'low', .7m above ground; 'medium', 1.4m; and 'high', 2.1m. These locations were measured for consistency using a marked pole. Cards were then clipped in pairs (one face up, one face down) with binder clips to leaves to simulate foliar exposure. Cards were collected after drying and placed in Ziploc (Dow Chemical Company, Midland, MI) bags labeled with location and treatment.

Cards were taped with clear packing tape on to white copy paper labeled with tree height, card orientation, and card height. A flatbed scanner was then used to digitize the cards and associated identification for further analysis. Adobe Photoshop Elements 8 software was used to differentiate water activated pixels (blue) and untreated pixels (yellow). Percentage of coverage was then calculated by dividing blue pixel count by total pixel count.

OBLR Bioassay

In order to record and compare the efficacy of pesticide delivery using the two delivery systems, Obliquebanded Leafroller (OBLR) bioassays were conducted using leaves from the same locations as the water sensitive paper was sampled and also from four separate untreated control trees. Each sample was tested against first instar OBLR. The larvae were exposed to the treated foliage 4 hours after application (drying time). For each of the sampling location (low, middle, and high) there were 5 leaves collected, equaling 15 leaves on each side of the tree (east, west), for 30 leaves total per tree. There were four leaf punches taken from each leaf. Moist filter paper (5.5 cm) was pressed into a 5 cm wide petri dish and the leaf punches (2.4 cm) were placed into the dish. The puncher was dipped in acetone between each tree location for sterilization. Five larvae were selected from different egg masses, to avoid genetic similarities, and placed on the punches spaced evenly within a dish. The dishes were sealed, labeled by treatment, and stored at a constant temperature and light intensity in a colony incubator at 27° C. After one week larval mortality was evaluated.

Pest Management Applications and Monitoring

Prior to the establishment of this experiment, insect pests and disease pressures had been conventionally managed in the planting. Trials evaluating pest and disease management efficacy were conducted throughout 2013 and 2014, utilizing a variety of agrochemicals delivered through the system. Each treated plot (SSCDS and air blast) received the same treatment on the same day.

TRECE Pherocon III Delta Traps and septa pheromone lures were used to monitor insect emergence and obtain counts. Population counts for Codling Moth (*Cydia pomonella* L.), Oriental Fruit Moth (*Grapholita molesta* Busck), Obliquebanded Leafroller (*Choristoneura rosaceana* Hodges), and Dogwood Borer (*Synanthedon scitula* Harris) were monitored weekly, and pest management decisions informed by catch results. Season long agrochemical applications for pest control in 2013 and 2014 (Table 2.1 & Table 2.2) were applied to the first six installed SSCDS rows, and then to the subsequent six rows when using the SSCDS. Sprays were split in this manner because the manifold was plumbed into the orchard from the center, and two main feed lines each fed half of the orchard, which precluded simultaneous spraying of both halves (see Fig. 2.1).

Pathogen presence and insect damage were assessed in ten randomly selected trees on the two treated rows in each plot at the midseason and pre-harvest intervals. Insect and scab damage to fruit was recorded in the 2013 mid-season and pre-harvest intervals, while in 2014 insect and apple scab damage was recorded for both terminals and fruit at the pre-harvest interval. In 2013, ten fruit per tree were sampled, five from the upper portion of the tree and five from the lower portion; in 2014, fifteen fruit per tree were sampled, five from the upper, middle, and lower strata of the tree.

Scab damage was assessed on a five point scale, with 0 being no damage and 5 as severe infestation. Obliquebanded Leafroller pupating in rolled leaves were recorded from terminals and clusters as well as feeding damage to adjacent fruit. Stinkbug feeding damage assessed based on the distinctive conical pits they produce, and grouped with Obliquebanded Leafroller fruit feeding damage as externally feeding pests. Codling Moth and Oriental Fruit Moth damage to fruit was recorded based on stings and larval entry tunnels and grouped as internally feeding pests. Plum curculio injury was logged based on feeding marks and their distinctive crescent shaped oviposition scar.

Spray Rates and Mixture

Coverage and OBLR bioassay sprays in 2013 and 2014 were made at a rate of 795 L ha^{-1} (85 g/A) in both systems, with SSCDS plots treated first and the remainder of the mixture applied through the air blast. Pumps pressurized lines to 276 kPa for the application, and six lines

Table 2.1 Formulations, rates, and type of chemical applications made through the air blast and solid set canopy delivery system in 2013.

Date	Product	Rate	Type
4/22/2013	Champ	6pt/acre	Fungicide
5/1/2013	Polyram	3lb/acre	Fungicide
	Captan 80wdg	2.5lb/acre	Fungicide
5/8/2013	Polyram	3lb/acre	Fungicide
	Captan 80wdg	2.5lb/acre	Fungicide
5/13/2013	Firewall	.5lb/100g	Streptomycin
	Fireline	1lb/100g	Oxytetracycline
5/15/2013	Polyram	3lb/acre	Fungicide
	Fontelis	20oz/acre	Fungicide
	Kasumin	2qt/acre	Streptomycin
5/20/2013	Firewall	.5lb/100g	Streptomycin
	Fireline	1lb/100g	Oxytetracycline
5/24/2013	Polyram	3lb/acre	Fungicide
	Fontelis	20oz/acre	Fungicide
	Assail	7oz/acre	Insecticide
5/29/2013	Polyram	3lb/acre	Fungicide
	Captan 80wdg	2.5lb/acre	Fungicide
6/3/2013	Polyram	3lb/acre	Fungicide
	Captan 80wdg	2.5lb/acre	Fungicide
6/7/2013	Polyram	3lb/acre	Fungicide
	Inspire Super	12oz/acre	Fungicide
6/13/2013	Altacor	3.5oz/acre	Insecticide
7/2/2013	Dipel	1lb/acre	Insecticide
	Latron	1oz/100g	Surfactant
8/5/2013	Calypso	6oz/acre	Insecticide

Table 2.2 Formulations, rates, and type of chemical applications made through the air blast and solid set canopy delivery system in 2014.

Date	Product	Rate	Type
4/23/2014	Champ	10lb/acre	Fungicide
4/30/2014	Polyram	3lb/acre	Fungicide
	Captan 80wdg	2.5lb/acre	Fungicide
5/7/2014	Polyram	3lb/acre	Fungicide
	Captan 80wdg	2.5lb/acre	Fungicide
5/14/2014	Polyram	3lb/acre	Fungicide
	Captan 80wdg	2.5lb/acre	Fungicide
5/19/2014	Fireline	1lb/100g	Oxytetracycline
5/21/2014	Polyram	3lb/acre	Fungicide
	Fontelis	20oz/acre	Fungicide
	Kasumen	2qt/acre	Kasugamycin
5/28/2014	Polyram	3lb/acre	Fungicide
	Captan 80wdg	2.5lb/acre	Fungicide
6/3/2014	Polyram	3lb/acre	Fungicide
	Captan 80wdg	2.5lb/acre	Fungicide
6/11/2014	Polyram	2lb/acre	Fungicide
	Inspire Super	12oz/acre	Fungicide
	Altacor	4oz/acre	Insecticide
	Calypso	4oz/acre	Insecticide
6/19/2014	Delegate	6oz/acre	Insecticide
	Firewall	.33lb/acre	Streptomycin
6/27/2014	Captan 80wdg	2.5lb/acre	Fungicide
	Flint	2oz/acre	Fungicide
7/9/2014	Altacor	3.5oz/acre	Insecticide
7/11/2014	Sevin	2.5qt/acre	Insecticide
7/25/2014	Delegate	6oz/acre	Insecticide
8/5/2014	Assail	6oz/acre	Insecticide
8/14/2014	Delegate	6oz/acre	Insecticide
9/25/2014	Assail	7oz/acre	Insecticide

delivered a spray that lasted for 12 seconds. This method applied a rate of 795 L ha-1, calculated so that the nozzles delivered the same volume per hectare as the airblast sprayer. Applications were a 300 gallon tank mix with water, Dipel (1.12 kg ha^{-1}), and Latron B1956 (.075g L^{-1}). Season long pest management sprays are listed in Table 2.1 and Table 2.2, and weather conditions are shown in Table 2.3.

Experimental Design and Statistical Analysis

The experimental design of the coverage measurements was a split-split plot in order to feasibly collect the data required. Sample height was considered the subplot factor, and orientation the sub-subplot factor. Analysis was performed in SAS 9.4® (SAS Institute Inc., Cary, NC, USA) using the PROC MIXED procedure. Proportion coverage from the cards on the east and the west sides of the tree was averaged and used as the response variable. Treatment, height, and orientation were all treated as fixed effects during analysis. Normality of the residuals was checked visually with normal probability plots and histograms of residuals. Residuals for each level of each factor were visually inspected with boxplots and Levene's test was performed to ensure that homogeneity of variance assumptions were met. Data from both years was arcsin transformed to meet assumptions of normality. Multiple comparisons for main effects and interactions were performed using the LSMEANS statement adjusted with Tukey's HSD and Tukey-Kramer test.

The experimental design of the Obliquebanded Leafroller measurements was set up as a split plot in order to feasibly collect the data required. Larval feeding mortality for the east and west sides of the row was combined. 'Height' was considered the subplot factor. Analysis was performed in SAS 9.4® using the PROC GLIMMIX procedure, fitting the data to a binomial distribution using a complementary log-log link function. Marginal likelihoods were approximated using Laplace’s method, and data from both years were analyzed together. Treatment, height, and year were all treated as fixed effects during analysis.

Pest management data was analyzed with a one factor ANOVA for 2013 mid-season counts, with the response variable expressed as damaged fruit per total checked fruit. Analysis was performed in SAS 9.4® using the PROC GLIMMIX procedure, with the model fit to a binomial distribution using a logit link function. Pest management data from 2014 was also expressed as damaged fruit/terminals per total sampled fruit and analyzed as a split plot design with a two-factor ANOVA - with treatment as the whole plot factor and height as the subplot factor. Apple scab data from 2013 and 2014 were also analyzed in PROC GLIMMIX, with the data fit to a binomial distribution using a logit link function.

Results

2013 Coverage

Coverage evaluations in 2013 compared the SSCDS and air blast efficacy, and showed a significant difference between the two application methods using a three factor ANOVA ($F_{1,6}$=33.37, p=.0012). Treatment and orientation was also a significant interaction term ($F_{2,18}$=46.58, p<.0001). Samples taken from the adaxial (upper) surface of the leaf showed no significant difference between the two treatments ($t_{\alpha=.05,18}$= -.30, adj. p=.99), while those taken from the abaxial (lower) surface of the leaf showed a significant difference ($t_{\alpha=.05,18}$= 8.86, adj. p<.0001), with higher proportions of coverage in the air blast treatments. The difference between adaxial and abaxial coverage within the SSCDS treatment was also significant ($t_{\alpha=.05,18}$= -5.18, adj. p=.0003), with higher levels of coverage on upwards facing cards. The air blast treated cards showed the opposite relationship, a significant difference between the adaxial and abaxial coverage ($t_{\alpha=.05,18}$= 4.47, adj. p=.0015), but with higher coverage on the underside of the leaf. No significant difference existed when comparing coverage from the air blast and SSCDS at the 'high' sampled height when taking into account coverage on both leaf surfaces ($t_{\alpha=.05,12}$ = 2.72, adj. p=.142), but significant differences existed in the middle and lower portions of the canopy ([middle] - $t_{\alpha=.05,12}$= 3.61, adj. p=.033; [low] - $t_{\alpha=.05,12}$= 4.34, adj. p=.009), with higher coverage from air blast treatments at both points.

2014 Coverage

Coverage evaluations in 2014 exhibited a markedly different outcome compared to 2013. No statistically significant differences were observed between the two treatments at the alpha=.05 level ($F_{1,6}$=5.00, p=.066), despite the large numerical difference in mean percent coverage, 33.8% and 15.6% for air blast and SSCDS respectively. Abaxial coverage in SSCDS and air blast treatments had a non-significant difference ($t_{\alpha=.05,18}$ = 2.02, adj. p=.218), and adaxial coverage showed the same trend ($t_{\alpha=.05,18}$ = 2.29, adj. p=.137). No other main effects or interactions were significant at the alpha=.05 level. (Figure 2.2).

OBLR Bioassay

Following larval feeding on bioassay leaf disks, mortality was assessed and recorded using a three factor ANOVA. Treatments were a significant factor ($F_{2,18}$=60.64, p<.001). The interaction of year and treatment as well as height and treatment were also significant ($F_{2,18}$=7.99, p=.003; $F_{2,36}$=14.68, p<.001). Multiple comparisons using the ESTIMATE statement and the Tukey-Kramer adjustment comparing mortality in air blast and SSCDS treatments

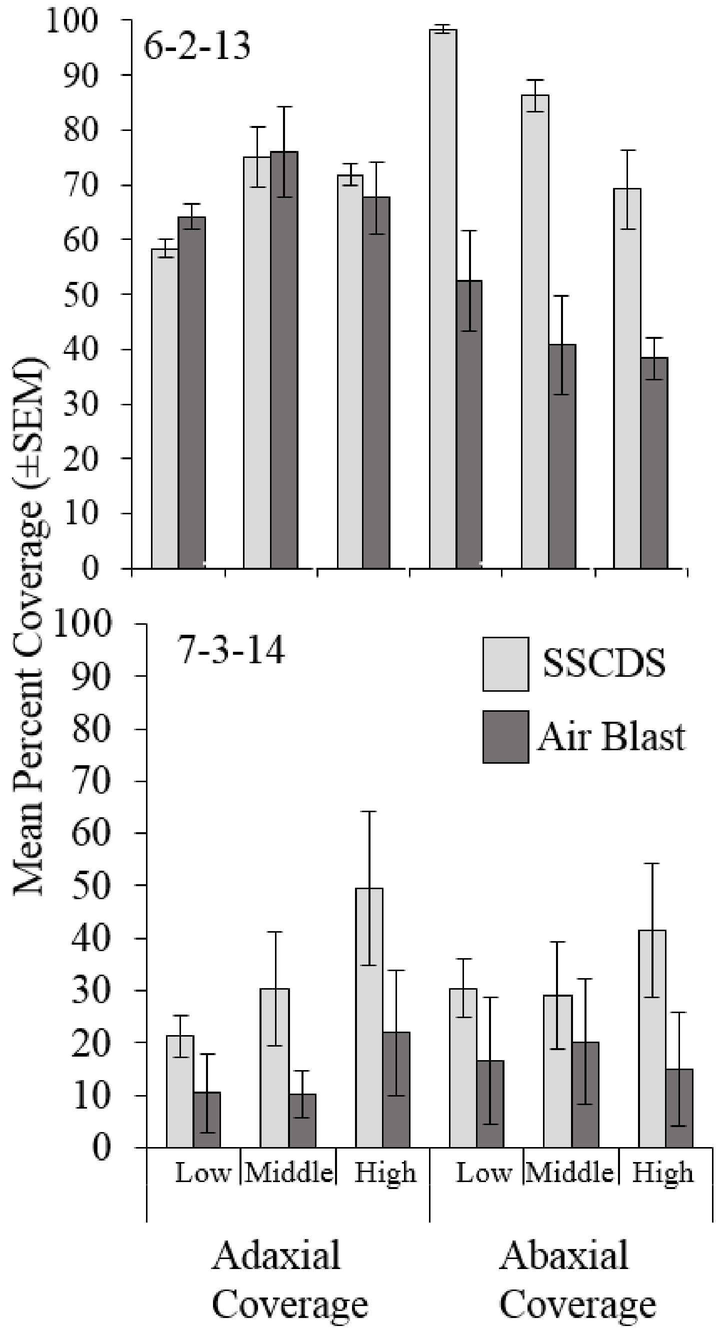


Figure 2.2 Mean (± SEM) percentage coverage on 6-2-13 and 7-3-14. Experimental treatments were Solid Set Canopy Delivery System (SSCDS) and Air blast. Adaxial (upper surface of the leaf) and abaxial (lower surface of the leaf) coverage for each treatment and height are expressed on the left and the right.

showed the air blast achieved significantly higher mortality in 2014 ($t_{\alpha=.05,18}$=3.22, adj. p=.046), but not in 2013 ($t_{\alpha=.05,18}$=2.32, adj. p=.235). Overall comparisons between the untreated control and the air blast also showed a significant difference ($t_{\alpha=.05,18}$=8.54, p<.0001), with air blast treatments displaying higher larval mortality. Significant differences were also observed comparing the untreated control and the SSCDS ($t_{\alpha=.05,18}$=9.45, p<.0001), with the SSCDS also exhibiting higher levels of larval mortality than the control. Overall untreated control larval mortality was 28.8% in 2013 and 39.8% in 2014. Mean mortality was highest in the 2013 and 2014 air blast treatments, with 100% of the OBLR reared on leaf discs from every height dying in 2014 and 100% mortality in 2013 at the highest sample height. However, at the points where air blast treatments did not display 100% mortality, they were statistically equivalent to the air blast treatments in the same year (Figure 2.3). Larvae fed on leaf disks treated by the SSCDS displayed 96.1% mortality in 2013 and 94.5% mortality in 2014.

2013 Pest Management

Fruit damage evaluations at the mid-season interval in 2013 showed no significant differences between the three treatments for externally feeding pests ($F_{2,9}$=.05, p=.952) or plum curculio damage ($F_{2,9}$=.12, p=.885). Only a single entry from an internally feeding lepidopteran was observed in the control treatment. At the pre-harvest interval, differences in externally feeding pest damage were non-significant at the alpha=.05 ($F_{2,9}$=3.15, p=.092), while internally feeding pests did show a significant difference by treatment ($F_{2,9}$= 11.27, p=.004). Multiple comparisons of internal feeders for the effect of treatment using Tukey's HSD show no significant difference between the air blast and SSCDS treatments ($t_{\alpha=.05,9}$= 1.03, adj. p=.577), but significant differences between the SSCDS and untreated control ($t_{\alpha=.05,9}$= -4.09, adj. p=.007)and the air blast and untreated control ($t_{\alpha=.05,9}$= -3.45, adj. p=.018).

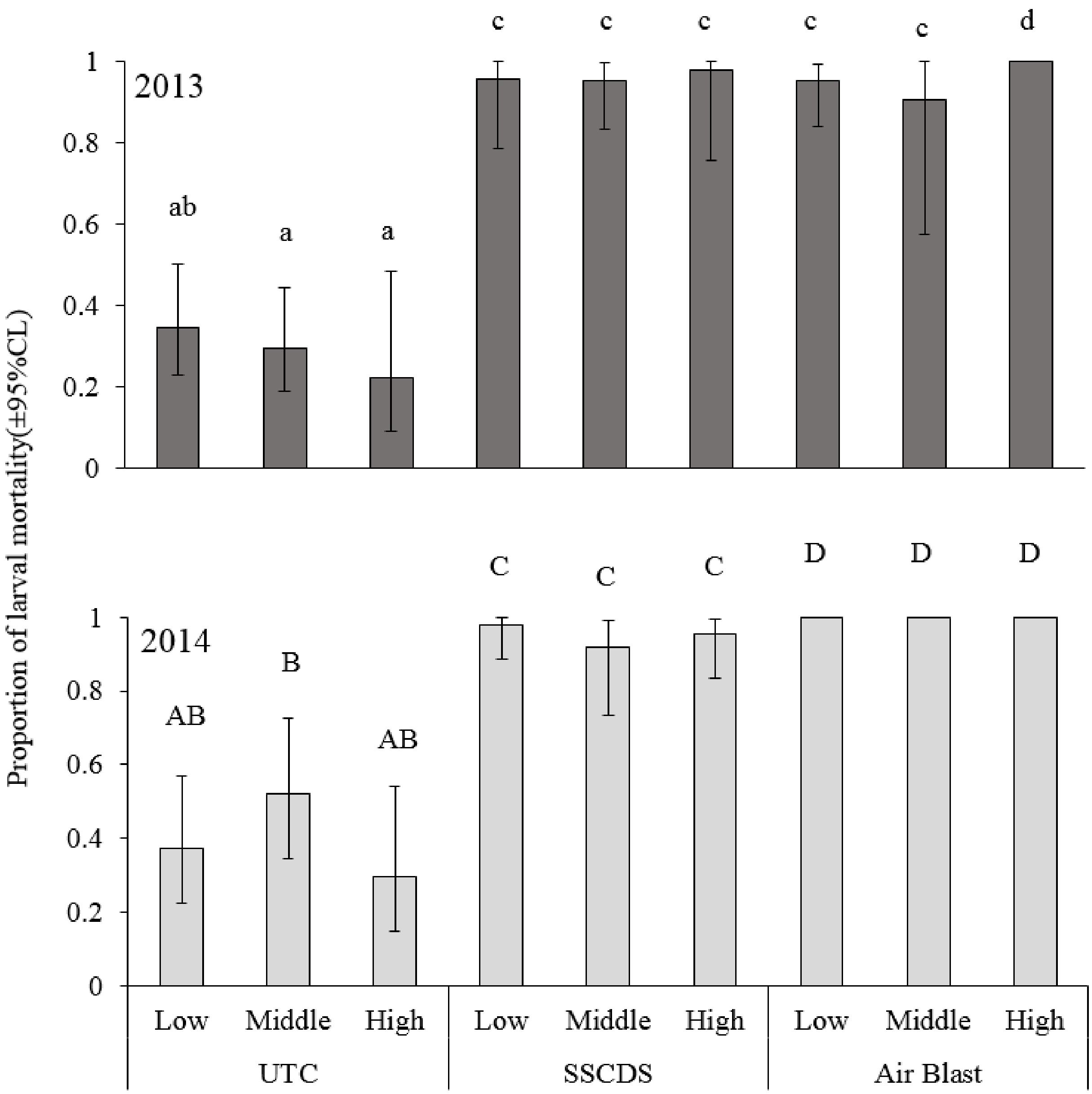


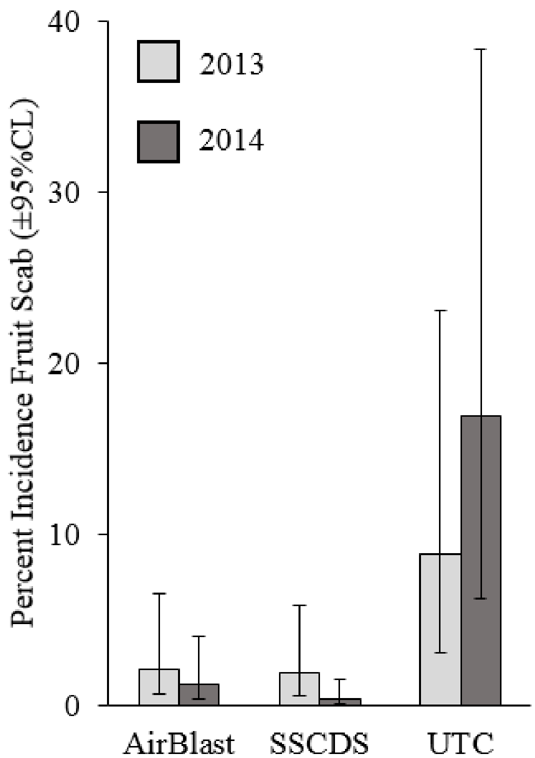
Figure 2.3 Least square means (± 95% confidence intervals) of the proportion mortality. Larvae were fed leaf disks from different heights post-treatment and reared in the laboratory for one week. Identical letters denote treatment means that are not significantly different. Means were analyzed on a complementary log-log scale and back transformed.

Only one instance of Plum Curculio feeding damage was observed at the end of the season in the untreated control, so comparisons could not be made (Figure 2.5).

Apple scab damage at the pre-harvest interval showed no significant differences in fruit scab between the three treatments ($F_{2,9}$= 3.21, p=.088) (Figure 2.4). However, foliar scab on the terminals, did show a significant difference by treatment ($F_{2,9}$= 13.78, p=.0018). Both the SSCDS and air blast treated plots had a significantly lower incidence of scab ($t_{\alpha=.05,9}$= -4.28, adj. p=.005; $t_{\alpha=.05,9}$= -4.74, adj. p=.003). The SSCDS and air blast treatments were not significantly different from each other ($t_{\alpha=.05,9}$= .657, adj. p=.891).

2014 Pest Management

Fruit damage evaluations at the pre-harvest interval in 2014 showed significant differences between the three treatments for externally feeding pests ($F_{2,9}$=8.54, p=.0088), internally feeding pests ($F_{2,9}$=5.07, p=.0335), plum curculio damage ($F_{2,9}$=5.31, p=.0299), fruit apple scab ($F_{2,9}$=16.81, p=.0009) (Figure 2.4), and terminal apple scab ($F_{2,9}$=7.09, p=.0142). Multiple comparisons using Tukey's HSD exhibited the same broad trend, a non-significant difference between air blast and SSCDS treated plots, and a significant difference between air blast and the untreated control and SSCDS and the untreated control (Figure 2.5). Damage in untreated control plots was higher than in the plots treated with the solid set canopy delivery system and the air blast, which showed no statistical difference. Multiple comparisons are summarized in Table 2.4.



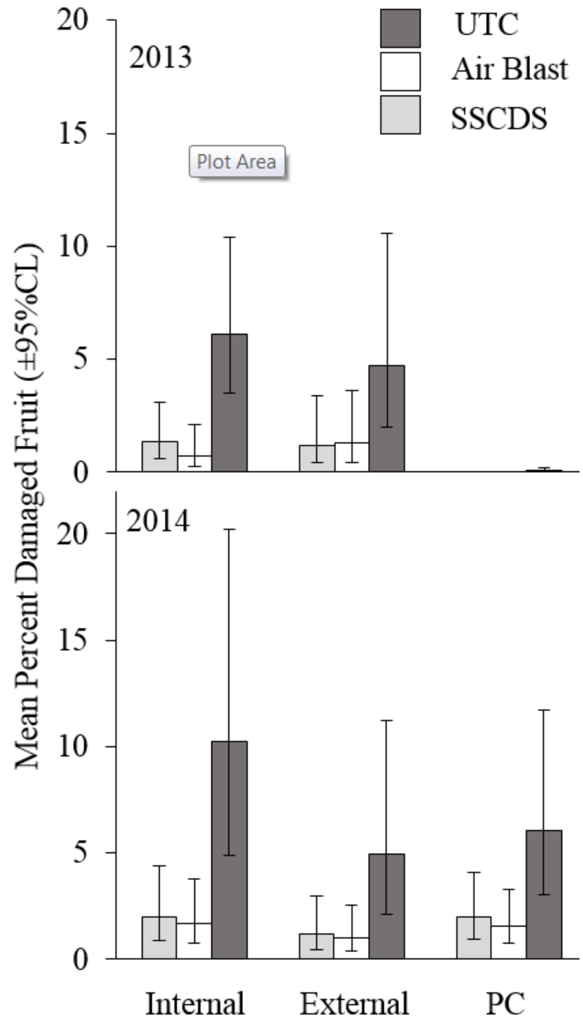


Figure 2.4 Least square mean (± 95% confidence intervals) percentage incidence of fruit apple scab lesions in the preharvest intervals in 2013 and 2014. Non overlapping confidence intervals in the same year denote significantly different means.

Figure 2.5 Least square mean (± 95% confidence intervals) percentage fruit damaged by arthropods from preharvest intervals in 2013 and 2014. Internally feeding pests were Codling Moth and Oriental Fruit Moth, externally feeding pests were Obliquebanded Leafroller and Stinkbugs, and PC was Plum Curculio feeding and oviposition damage.

Table 2.3 Environmental conditions on the two spray dates.

Date	Time	Temp (°C)	Relative Humidity (%)	Wind Speed (m/s)	Max Wind Speed (m/s)	Wind Direction (° from N)
6/2/2013	10:00	12.3	93.5	3.8	7.8	291.7
	11:00	10.9	89.1	4.2	7.5	299.9
	12:00	10.4	87.1	3.5	7.7	300.5
	13:00	11.4	82.6	3.2	7.7	293.6
	14:00	12.1	78	3.5	6.5	299.6
	15:00	12.7	74.8	3.3	6.7	296.5
7/3/2014	10:00	12.1	86	1	3.5	254.9
	11:00	14.4	76.1	2.2	5.5	314.9
	12:00	16.9	63.2	2.7	5.5	316.1
	13:00	18.7	50.1	2.8	5.8	289.5
	14:00	19.6	45	3.4	7.4	311.1
	15:00	20.6	45.3	3	7.2	303.8

Table 2.4 Multiple comparisons between least square means of incidence of pre-harvest pest damage in 2014. P values for multiple comparisons adjusted with Tukey-Kramer method. Asterisks denote a significant difference at the alpha=.05 level

	Damage Type									
	Fruit								Terminal	
	Internal		External		PlumCurculio		Apple Scab		Apple Scab	
	t value	Adj. p	t value	Adj. p	t value	Adj. p	t value	Adj. p	t value	Adj. p
Air Blast/ Control	-3.39	**.012***	-2.59	**.068**	-2.52	**.076**	-4.38	**.005***	-3.59	**.006***
SSCDS/ Control	-3.70	**.019***	-2.86	**.045***	-3.02	**.035***	-5.48	**.001***	-2.78	**.021***
SSCDS/ Air Blast	.32	**.947**	.28	**.959**	.51	**.867**	1.09	**.541**	-.80	**.443**

Discussion

Data were collected for two successive years to compare the spray coverage and pest management using a novel agrochemical delivery method, the solid set canopy delivery system (SSCDS), and a conventional tractor-driven radial air blast sprayer. Results in 2013 showed that the SSCDS coverage on the upper side of leaves was equivalent to the air blast, but that the air blast demonstrated superior coverage on the under-side of the leaf. Subsequently, in 2014 differences in the level of coverage were not significantly different. Additionally, mean levels of coverage at each of the sampled heights were lower in both systems in 2014. These results provide some evidence that refutes our original hypothesis, that the SSCDS and the air blast provide equivalent coverage, specifically on the underside of the leaf.

Spray coverage is heavily dependent on the density and developmental stage of the canopy (Giles et al. 1989, Herrington et al. 1981, Cross et al. 2001a, 2001b, 2003), a thicker canopy with more leaf surface area will intercept more spray and exhibit decreased spray penetration. Apple trees typically reach maturity 4 to 10 years after planting (Flore et al. 1984), with the orchard in question established in 2009. The vegetative development of the trees as they continued to mature from 2013 to 2014 produced a denser canopy. This increased canopy density would have occluded more spray that was emitted from the microsprayers, resulting in less overall coverage. Coverage tests in the final year were also conducted a month later (early July rather than early June) than measurements in the previous year. This would have also given the trees more time for terminal shoot and leaf growth, leading to a more expansive canopy and a more complex spray environment. Canopy features such as total leaf surface area and tree volume have a significant impact on the amount of spray that reaches the target (Duga et al. 2015).

Another possible contributor to the decreased coverage in 2014 may have been the reduced wind speed. Spray produced by the SSCDS appears to be a slowly falling mist, which is easily influenced by the wind. In 2013, average wind speed was about twice as high than in 2014. Air movement also ran across the row from the west in both years (Table 2.3), rather than down the row, which may have helped move spray from one row to another. Higher wind speeds in 2013 may have carried droplets over to the next row before they settled out of the air, and improved the coverage since it countered sedimentation in still air. If this was the case, it would run counter to spraying guidelines which call for sprays in weather that is calm as possible. SSCDS systems may actually get enhanced coverage with more local air movement. Small droplets may have had a greater chance of impacting a surface and sticking. However, this may come at the cost of coverage on the lower surface of the leaf. While sprays in 2013 showed lower coverage, they also had statistically equivalent coverage on the upper and lower surfaces of the leaf. Small droplets that are influenced by air currents may have had more time to move around within the canopy and contact the underside of leaves with the lower levels of air movement in 2014, but at the cost of overall coverage. Degradation or clogging of the microsprayer nozzles may also be a contributing factor, since they had been in place for three growing seasons. Pesticide residue, dust, or bacterial colonization of the .8mm aperture on the nozzles that were left in situ may have partially blocked or distorted the water jet that leaves the emitter. Deformation or residue accumulation from these same sources on the deflection pad would also negatively impact the distance and angle droplets are redirected at.

The nature of an air blast would have partially mitigated the issue of canopy density dependent coverage, since the droplets are carried in a large, moving cloud of air throughout the tree (Duga et al. 2015). This air-jet pushes spray particles through the canopy, while the SSCDS relies on pressure and gravity to disperse and apply the droplets. If a local point source (a single emitter) of spray is occluded by a branch or leaves, then the surrounding area is likely to receive less spray. This seems to also explain the SSCDS's lower coverage as measured by the water sensitive cards placed on the underside of leaves. This disparity is consistent across each of the sampling heights, and obvious at every sampled date. Once a droplet loses its pressure-derived velocity it is subject to the motion of air currents and gravity. Small aperture nozzles utilized in this experiment were selected for a 'fine' (ASABE S-572.1 Standard, 2009) droplet spectra with a DV0.5 (median diameter) equal to ~180 microns (Ledebuhr, unpublished). These small droplets have far less kinetic energy than a coarse spray and are therefore subject to either gravity or air currents that move them horizontally or vertically (Koch et al. 2004). Without moderate ambient air movement, the larger droplets of the spray settle and begin to fall downwards. This showers the upper surface of the leaves, and while half the spray is directed upwards by the radial ridges on the deflection plate, a portion of the spray that begins travelling aloft vertically will succumb to gravity and rain down. This effect leads to a higher overall proportion of the spray coming from above the leaf surface. Leaves that receive coverage on the underside must be placed near a microsprayer or receive deposition from the fine spray droplets that have wafted through the canopy due to air movement.

Despite the differences in coverage between the air blast and SSCDS, and differences from year to year, the tested pest management efficacy of the two systems was near equivalent when tested with a leaf disk bioassay in 2013 and 2014. Obliquebanded Leafroller bioassays showed no statistical difference between the two treatments in 2013, with a highly significant difference between the two treatments and an untreated control. In 2014, there was a difference in the two treatments, since there was complete larval mortality at all three heights. However, mean SSCDS larval mortality was still nearly 95%. This indicates that despite inferior coverage from the SSCDS, treated leaves still receive enough active ingredient for pest suppression. A paper by Holownicki et al. from 2002 suggests that 30% coverage is typically adequate for most insect pests, while mean SSCDS coverage in 2013 and 2014 ranged between 10-75% when the OBLR bioassay was performed. Even at points with the lowest coverage in 2014 – SSCDS treated foliage at the 'low' and 'medium' strata – mean OBLR mortality was still above 90% with leaf coverage around 10%. The difference in management in 2014 may be attributed to the reduced coverage that year compared to 2013, and the fact that since OBLR mortality in air blast treated plots was 100%, there was no variance.

In order for a solid set canopy delivery system to be considered a viable alternative to the established standard of air blast spraying in orchards, it needs to maintain a similar or better level of pest management efficacy. Despite the variable coverage results, and inferior spray distribution in some cases, the SSCDS still produced statistically equivalent protection in leaf disk bioassays in 2013, and very similar mean mortality in 2014. Additionally, season long pest management showed no difference between the two years. The Obliquebanded Leafroller response to the pesticide deposition in the bioassay may be different to that of a pest that enters the apple at a single point, spends less time on the surface of leaves or fruit, or is controlled with a contact pesticide. However, pre-harvest pest damage data showed no significant differences between the air blast treated plots and the SSCDS plots in regards to internally feeding lepidopterans, externally feeding insects, and plum curculio. These findings, contrasted with the highly significant difference between damage in treated and untreated plots indicates that the SSCDS provides comparable levels of insect control. Similarly, season long disease management for both fruit and terminal leaf apple scab, the primary fungal disease managed by Michigan growers, showed comparable results between the two systems.

These finding suggest that with further engineering and optimization, an SSCDS would achieve parity or even outperform an air blast in terms of coverage and pest management. Despite the advantage of nearly a century of tinkering and production, an air blast lacks many of the benefits an SSCDS provides in addition to its spray capacity. Microclimate management (Hanrahan et al. 2014), irrigation and foliar nutrient inputs, less orchard traffic and soil impaction, and a rapid tool for precisely timed inputs give the SSCDS additional value that should be considered.

Understanding how the SSCDS works in large, orchard size plantings would be the next logical question to ask. So far, most recent research has focused on optimizing emitter style, orientation, spacing, and the mechanics of spray delivery (Sharda et al. 2014, Sharda et al. 2013, Panneton et al. 2011, Agnello and Landers 2006) Since the current research presented here was conducted in pairs of rows with an SSCDS installed, pest management and spray coverage levels might be improved when the sampled area is completely surrounded by a microsprayer array covering a square instead of linear block. Additionally, more work looking at the optimal line length, diameter, and operating pressure may be needed to ensure an even distribution of spray across the entirety of the treated area.

CHAPTER THREE – SEASON LONG SPRAY CHARACTERISTICS AND PEST MANAGEMENT EFFICACY OF A SOLID SET CANOPY DELIVERY SYSTEM

Introduction

A Solid Set Canopy Delivery System (SSCDS) is a novel agrochemical application technology for high-density fruit production. A series of stationary microsprayers are distributed throughout the orchard, linked by a network of delivery lines to a manifold where an operator controls the application. This technology promises a rapid and precise method of chemical application, while removing the personnel and heavy machinery from the orchard environment. This stands to minimize worker chemical exposure that occurs during spraying (Hall et al. 2002; Moon et al., 2013; Matthews et al., 2014) as well as damage to trees from accidents and soil compaction (Håkansson et al., 1988; Ferree et al., 2004; Becerra et al., 2010). Fixed emitter applications have been investigated sporadically for decades, beginning with the original concept of using overhead frost protection sprinklers as an agrochemical delivery system, but were limited by the components and materials available (Lombard et al., 1966). Recent research by Agnello and Landers (2006) overcame many of the early issues by utilizing higher densities of low cost plastic micro sprinklers and pressure controlled valves. This proof of concept has been expanded on by Sharda et al. (2013, 2015), and Owen-Smith (2017), suggesting that a SSCDS could replace air blast spray application in high-density orchards.

The transition to high-density fruiting walls has created a planar tree architecture that is tall and narrow, resulting in a porous boundary unsuited to the high speed air and chemical mixture emitted by axial fan radial air blast sprayers that are used by most orchard growers (Herrington et al., 1981; Byers et al., 1985; Holownicki et al., 2000). This thin canopy profile, in conjunction with problems that are inherent to the air blast sprayer's design, results in many growers over-spraying the lower and middle portion of the canopy and under-spraying the top level of the trees (Brann, 1956; Derksen & Gray, 1995; Holownicki et al., 2000). Extensive research into off-target deposits has shown large amounts of chemical applied by air blast sprayers are wasted when they are discharged into the local environment and atmosphere (Herrington et al., 1981; Cross, 1991; Doruchowski et al., 1997; Cross et al., 2003; Landers, 2011). These issues are exacerbated by sprayers that are poorly calibrated, and many growers do not adjust nozzle apertures, angles, or spraying speed to the variations in tree size, cultivar, spacing, or phenological stage often enough during a season, and instead use a 'one size fits all' approach (Holownicki et al., 2000, Cross et al., 2001). Furthermore, pesticide labels often only contain information on recommended dosages as quantity per hectare, which can result in up to a tenfold difference in average dose per area of canopy (Drew, 1996; Furness et al., 1998). These issues have led to the resurgence in interest in an optimized fixed spray system, but any design must achieve parity with air blast sprayers in order for it to be commercially viable.

Comparing a traditional air blast sprayer and solid set canopy delivery system requires measures that quantify spray efficacy. There are two main approaches to testing spray systems: observing pathogen and disease suppression, or measuring spray deposits and coverage (Holownicki et al., 2002; Wise et al., 2010). Deposition and coverage measurements are a proxy that provide information that allow the researcher to draw inferences on pest management, and track seasonal changes as the canopy develops. They are closely related, but provide information on different aspects of spray quality.

Deposition measurements determine the quantity of a chemical sprayed onto a surface, expressed in mass per area. Targets are sprayed with a tracer compound, and then collected and washed to recover the applied material. An effective method to quantify the recovered tracer utilizes absorption spectrophotometry and dye. Error is minimal for high enough concentrations (above 1 mg L^{-1}) and recovery variation is low on different surfaces, such as leaves or paper (Pergher, 2001; Sánchez-Hermosilla et al., 2008). Coverage measurements describe the extent of the treated area, expressed as a proportion of the surface that receives treatment or contacts dropets (Holownicki et al., 2002). Coverage demonstrates the extent of the treated area as well as the uniformity and quality of the spray, but lacks information on the total amount of chemical retained on target surfaces. Target cards that change color when contacted by droplets are placed within the canopy to mimic leaves, and then sprayed in a simulated application. Spray coverage has been used extensively in previous research into solid set canopy delivery systems (Lang & Wise, 2010; Sharda et al., 2015; Verpont, 2015) and in tracing spray deposits from air blasts (Salyani & Fox, 1999; Cross et al., 2001 a,b, 2003; Holownicki et al, 2002). Representational measurements that stand in for pest management allow for rapid assessment of various nozzle styles and configurations (Sharda et al., 2014), as well as characterizing the overall system performance.

Agnello and Landers made improvements to earlier SSCDS design iterations by utilizing modern greenhouse microsprinkler components in a fixed spray system at the New York State Agricultural Experimental Station in 1998 (Agnello & Landers, 2013). Components were selected for smaller droplet sizes due to research showing they had excellent coverage (Hodgson, 1990; Bode, 1981). Preliminary trials demonstrated equivalent control of arthropod pests and pathogens to that obtained by the air blast over the two years the study was active, however these first experiments were limited in size (Agnello, 2007). Experiments in 2005 and 2007 also demonstrated equivalent insect and disease control, with no significant differences in damage or yield (Agnello & Landers, 2006).

A similar system was evaluated at Michigan State University (MSU) in 2007 using five types of suspended microsprinklers and foggers to test spray coverage on cherry trees under protected culture. Only partial coverage was achieved and it was reported that there was very little spray coverage on the underside of leaves at all sampled heights (Lang and Wise, 2010) – which has been a persistent trait of all the tested solid set canopy delivery systems using microsprinklers thus far. This system relied on a single emitter above each tree, and the authors suggested that additional emitters within the canopy might resolve the under-coverage within the middle of the canopy and on the underside of the leaves. This prompted further research in apples and cherries at MSU and Washington State University (WSU). Research in high density apples at MSU demonstrated that arrays of microsprinklers placed above as well as within the canopy offered the same level of protection as an air blast sprayer. Coverage trials continued to show that there was less coverage on the underside of leaves, but the additional microsprayers within the canopy increased the amount of coverage at low and middle canopy tiers (Owen-Smith, 2017).

Further SSCDS coverage evaluations of apple and cherry orchards in Washington showed that the air blast provided better coverage overall, as well as higher chemical deposition. In apples, coverage on air blast treated spray cards was 55% higher. Abaxial and adaxial coverage corroborated previous findings; the air blast gave 80% more coverage on the underside of spray card pairs. Droplet patterns measured by water sensitive spray cards also showed more uniform coverage in air blast treated plots. Chemical deposition trials showed that the SSCDS delivered 8.7µL/cm2 of product compared to the 39.9µL/cm2 collected from air blast treated leaves (Niemann & Whiting, 2014). Similar experiments in Quebec and France using SSCDS's in high-density apples suggested perfect (even and extensive) coverage was not required for effective disease and pest suppression. The three nozzle and emitters tested deposited varying amounts of spray within different tiers of the canopy, but pathogen and pest damage was near equivalent. Authors speculated that pesticide efficacy simply requires sufficient coverage for pest control, rather than an absolute threshold, determined by pest type and ambient conditions (Panneton et al., 2011 & 2015). French systems showed more heterogeneous spray deposits in SSCDS treated trees, yet both air blast and SSCDS had comparable efficacy in suppressing apple scab, with significantly less scab than untreated blocks – 3% in both treated areas versus 98.5% in untreated (Verpont et al. 2015).

Separate lines of research into Solid Set Canopy Delivery Systems have exhibited several common themes- lower levels of coverage on abaxial leaf surfaces, more heterogeneous coverage than air blasts, but similar levels of insect pest and pathogen suppression. However, to our knowledge, none of these experiments combined large-scale orchard plots, robust subsampling and replication, and temporal repetition with coverage and deposition measurements as well as season long pest management. Previous studies have been limited in one or more of these aspects, and each of these components is required for a more comprehensive understanding of how a solid set canopy delivery system compares with a traditional axial fan air blast over the course of a growing season. Consequently, this study was designed to address these components together by directly comparing the overall pest management of the SSCDS with an air blast, and quantifying the spray coverage and deposition within the canopy. Treatments were applied in field scale multi-row square orchard plots and assessed at several stages in order to obtain results that were representative of a commercial system. The specific objectives of this project were:

1. Quantify spray coverage on both the upper-side (adaxial) and under-side (abaxial) of leaf surfaces at different levels within the canopy and at multiple time points using water sensitive cards.
2. Assess spray deposition on leaf surfaces at different levels within the canopy at multiple time points using a tartrazine tracer dye and absorption spectrophotometry.
3. Evaluate season-long pest management of the SSCDS and its ability to suppress arthropod pests and plant pathogens compared to an air blast sprayer through damage evaluations.

Materials and Methods

Spray System

Solid Set Canopy Delivery System

The canopy delivery system was comprised of upper (2.5 cm) and lower (1.9 cm) Blue Stripe® Poly Tubing polyethylene hoses (The Toro Company, Bloomington, Minnesota, United States). Hoses formed a continuous loop, with the 2.5 cm line running 107 m down length of the orchard attached to the trellis wire with clips at 2.6 m. Hoses then dropped down and returned along the trellis wires at 1.2 m, with a reduction in line diameter to 1.9 cm.

NaanDanJain Irrigation Ltd. (Na'an, Israel) manufactured all microsprayer components used in the system. Hadar 7110 series microsprinklers with 'black' .08mm nozzles and 'yellow star' static spreaders were selected for fine droplet sizes. Individual components had injection molded bayonet style attachments, custom made for the project by NaanDanJain at the request of TRICKL-EEZ (Figure 3.1). Pieces locked together with a half twist, an advantage over friction attachments, which were prone to decoupling when the system was pressurized. Previous prototypes were built as a ‘direct injection’ style system. Single or double emitters were fitted onto 124 kPa Leak Prevention Device (LPD), and then plugged into both the upper and lower lines. In contrast, this system’s individual emitter unit was an array of three microsprayers attached with thin tubing to a single LPD inserted into the upper delivery line. This arrangement allowed movement and arrangement of microsprayers within the canopy to better positions, preventing occlusion by foliage. Plugging emitters solely into the top line rather than both the upper and lower lines also mitigated any issues with pressure drop off from the length of the loops and hydraulic friction. The previous system had sets of double emitters on the bottom line that were effectively more than 215 m away from the pumps due to the loop that the fluid made, which caused a notable pressure drop (Owen-Smith, unpublished data). The pressure rating on the LPDs in the new system was raised since the strength of the bayonet style connection allowed for higher operational pressures - resulting in quicker charging period and faster sprays.

A single microsprayer was attached to the top delivery line using a hose clip with a horizontal pillar that held the microsprayer perpendicular to the row at intervals of approximately .9 m. Two additional microsprayers were mounted to a ‘T’ fitting with bayonet attachments and were wired to the second trellis wire at 1.2 m also spaced approximately .9 m apart. The single emitter on the top line and the pair on the bottom line were attached with 6.35 mm/4.35 mm (outer/inner diameter) polyethylene ‘spaghetti’ tubing to a single 240 kPa LPD that was then plugged into the upper 2.5 cm line with a barb (Fig. 3.1). The emitters on the top and bottom lines were offset such that they fell in between the two emitters above or below them, with a microsprayer on either the top or bottom line every .9 m.

The application equipment consisted of; a pumping system, an air compressor, and a tank

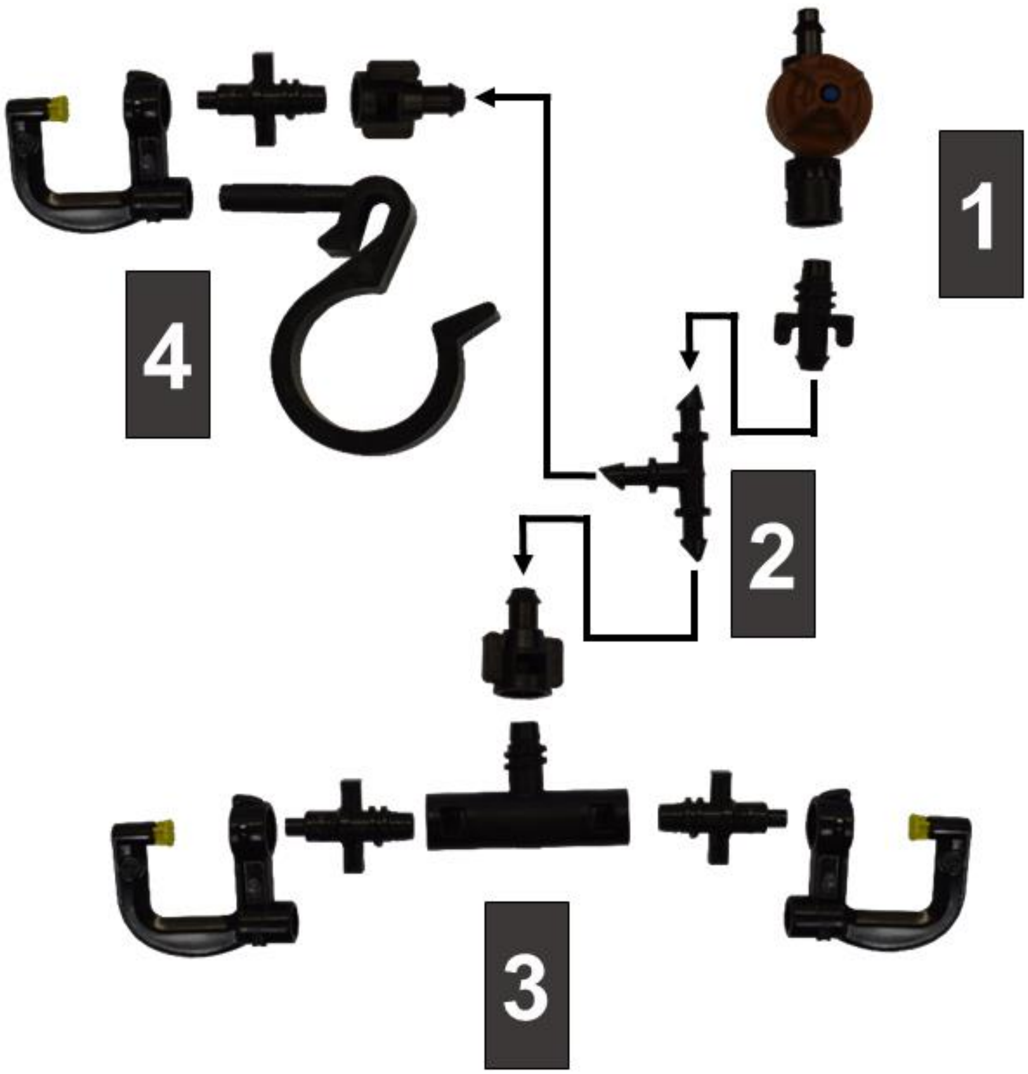


Figure 3.1 Microsprayer components for a set of sprayers. (1) 241 kPa Leak prevention device that is inserted into 2.5cm upper line with bayonet adapter to .635 cm line. (2) 3 way split inserted into .635 cm line. (3) ‘T’ bayonet fitting attached to a pair of .8mm nozzles and Hadar 7110 spray deflectors. (4) Single microsprayer fixed to post on hose/wire clip.

for providing and recapturing excess spray material from the system. Two tandem pumps powered by Honda GX160 160cc engines provided line pressurization and chemical delivery. Spray formulation were drawn from the holding tank, a REARS Powerblast Sprayer (REARS MFG. CO., Coburg, Oregon, United States) with a 1892.7 L capacity, and then pumped through the manifold, along the main line, and up into lateral lines. Filling lines was completed while keeping the pumping pressure under the minimum spray pressure of the 240 kPa LPDs, typically around 195 kPa. Once fluid had completely filled the system and was flowing back to the tank return line ball valves were shut to close the loop and seal lines pressurization to application levels. Lines were sprayed in sets of three- nine lines were plumbed into each half of the manifold, with three sprays ten second spraying events required to cover each half the orchard, for a total of six spraying events to cover the entire SSCDS treated area. Spraying in sets of three mitigated issues with pressure drop-off and allowed for more consistent and accurate spray delivery. Pumps throttled up until the lines were pressurized to 415 kPa for the application, and each group of three lines delivered a spray that lasted for 10 seconds. This method applied a rate of 655 L ha^{-1}, calculated so that each individual nozzle emitted 132.36 ml. This spray volume was confirmed with a volumetric test that demonstrated average nozzle output was 132.3 ml (Owen-Smith, unpublished data).

After sprays were completed, return line valves were opened and excess fluid in the lines was pneumatically purged with a diesel air compressor (D185PJD Sullivan Palatek, Michigan City, Indiana, United States) at a pressure lower than that required to overcome the LPD on each emitter (240 kPa). Fluid flowed through the output line and back into the holding tank of the air blast sprayer (Fig. 3.2). The recirculated and remaining plant protectants were then applied through the REARS Powerblast air blast sprayer to comparison plots. The REARS was outfitted

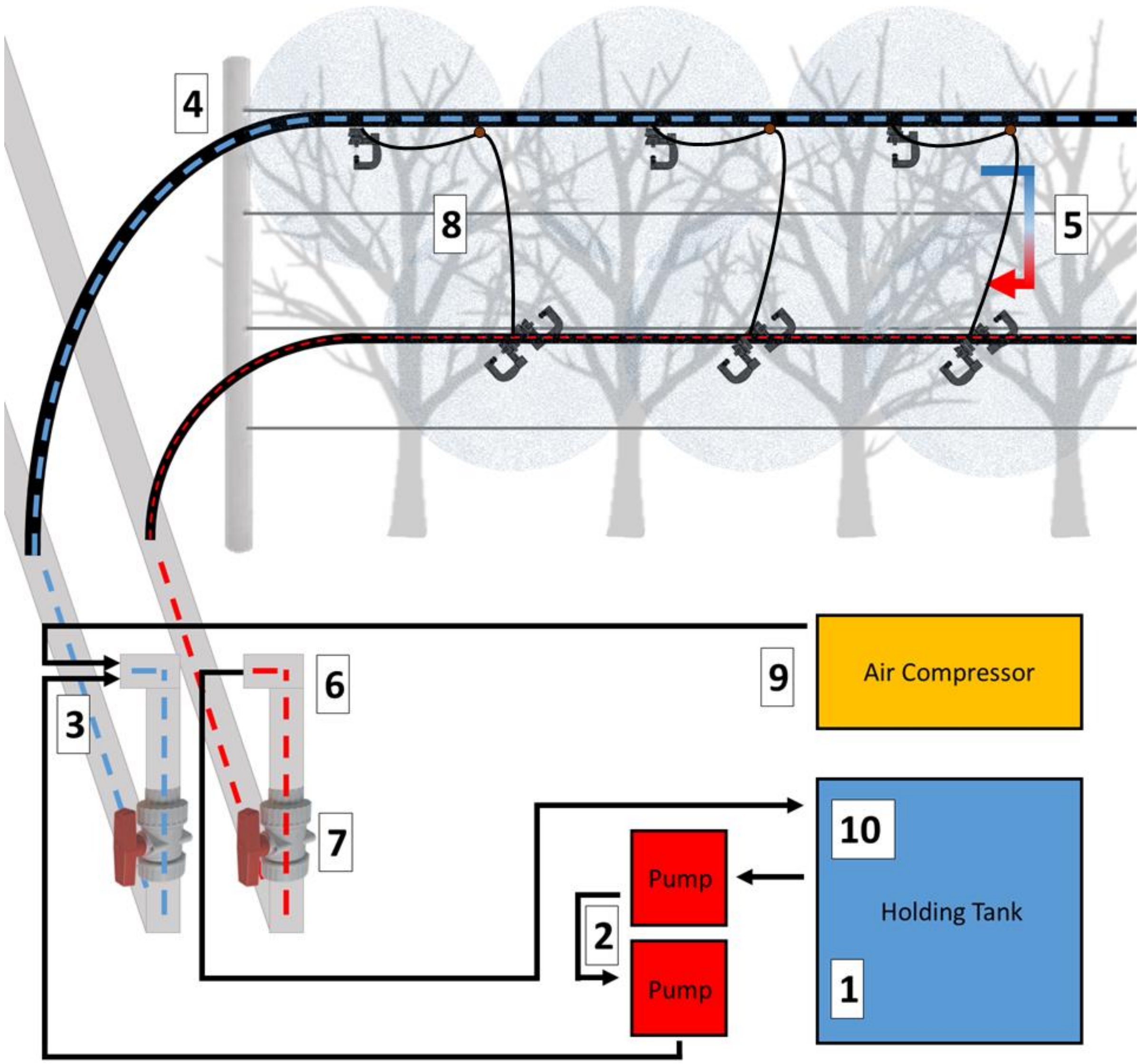


Figure 3.2 Schematic of 2016 Solid Set Canopy Delivery System-
1. Spray material mixed in holding tank.
2. Liquid mix is drawn out of tank and through tandem gas powered pumps.
3. From the pumps, mix is impelled up to manifold at <240 kPa and underground into 5cm diameter PVC lateral lines in front of the orchard.
4. Once PVC lateral lines are filled, liquid moves up into 2.5cm polyethylene delivery lines.
5. Spray material fills top line, and then begins to return in 1.9cm bottom hose.
6. Circulated liquid is returned to holding tank and lines are filled with spray material.
7. Return valve is closed, and pumps increase pressure to 415 kPa, overcoming the 240 kPa LPD.
8. Spray is applied through emitters for 10 seconds.
9. Return valve is opened, and air compressor fills lines with air, pushing the excess spray material through the loop.
10. Once lines are emptied back into holding tank, air pressure is increased to purge the remnants of spray from the line and residue from the nozzles.

with 23CER ceramic cores and DCER4 ceramic orifice discs, and also applied at a rate of 655 L ha^{-1}.

Experimental Area

Experimental plots were established in a mixed variety apple (Malus domestica) orchard at Michigan State University's Clarksville Research Center (CRC), in Clarksville, Michigan. The five year old planting was established as 24 rows, each 137 m long, with eight rows each of three varieties 'Crimson Royalty Gala' on M.9 rootstock; 'Honeycrisp' on B.9 rootstock, and 'Rubinstar Jonagold' on B.9 rootstock. Trees were trained to the tall slender spindle system at a .9m in-row spacing and 3.35m between-row spacing. Planting density was 3720 trees ha^{-1}.

Eight experimental units were established in the orchard: four air blast plots, and four solid set canopy delivery plots in a randomized complete block design. Each plot consisted of 306 trees – 102 of each variety. Plots were .09 hectares: nine tree rows wide and 34 trees long, established as squares that were approximately 30 m on each side. Each plot was surrounded by a 4.5m buffer area on the north south axis to prevent spray movement down the row from one plot to another, and a 9m buffer area on the east west axis to prevent spray movement across rows. No sampling points were on the periphery of the plots to ensure samples were unaffected by other treatments (Fig. 3.3). All data were collected in 2016, coverage and deposition samples were collected on May 2nd, June 8th, July 12th, and August 8th. Weather conditions are summarized in Table 3.1, but differed little between treatments.

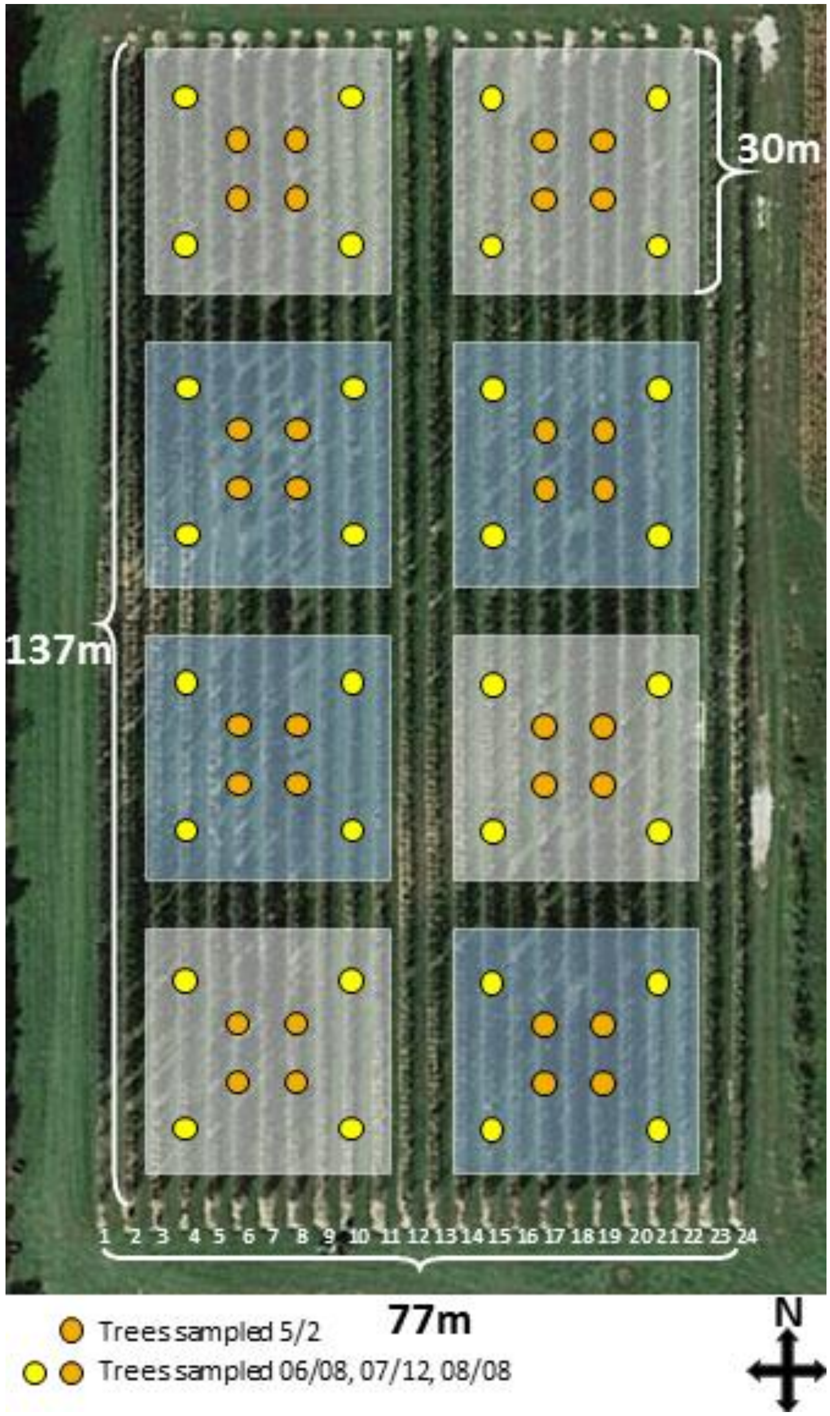


Figure 3.3 Plot plan of the SSCDS orchard installation. Blue shaded squares denote SSCDS sprayed plots, white squares are air blast plots. Yellow and orange markers are the approximate location of sampled trees.

Table 3.1 Environmental weather data from Clarksville Research Station's Enviro-weather station on spray evaluation days. Wind came from the E/NE in May, W/NW in June, S/SW in July, and E/SE in August

Date	Time	Air Temp (°C)	Precip. (mm)	Relative Humidity (%)	Wind speed (m/s)	Max Windspeed (m/s)	Wind Direction (° from N)
5/2/2016	10:00	6.8	0	83.3	0.6	2.9	54.3
	11:00	8	0	77.2	0.9	2.5	67.7
	12:00	9.6	0	74.7	0.8	2.8	60
	13:00	10.3	0	72.7	0.7	2.6	81.8
	14:00	11.7	0	69.1	0.8	2.9	60.9
	15:00	12.7	0	66.2	0.6	2.5	68.7
	16:00	12.6	0	66.8	0.5	2.3	76.4
6/8/2016	10:00	11.4	0	70.9	3.3	6.5	299.7
	11:00	12.8	0	59.1	3.8	7	296.2
	12:00	14.1	0	53.4	3.3	6.5	287.2
	13:00	15.1	0	51	3.3	6.7	294.5
	14:00	16.2	0	49.8	3.4	7.4	291.1
	15:00	17.3	0	47.4	3.2	6.5	297
	16:00	18.2	0	44.1	4.1	9.1	287
7/12/2016	10:00	24.8	0	70.1	2.3	5.8	197.7
	11:00	26.6	0	65.6	2.4	5.2	198.7
	12:00	27.9	0	63.9	2.7	6.2	200.4
	13:00	29	0	61.3	2.4	5.8	189.5
	14:00	30.4	0	55.8	2.5	7.1	184.9
	15:00	30.1	0	54.8	2.4	6.7	182.5
	16:00	31.1	0	51.8	2.8	8.4	189
8/8/2016	10:00	19.6	0	81.9	0.5	2.1	106.8
	11:00	22.6	0	64	0.7	2.6	131.3
	12:00	24.8	0	52.1	0.8	2.8	95.5
	13:00	26.1	0	46.2	0.7	3	84
	14:00	26.6	0	42	0.7	2.8	104.1
	15:00	27.5	0	39.4	0.8	3.4	103.1
	16:00	27.9	0	39.2	0.7	2.9	62.6

Coverage, Deposition, and Insect and Disease Damage Evaluations

Coverage

Coverage was recorded and quantified using water sensitive paper (WSP) cards (TeeJet®, Spraying Systems Co., Wheaton, IL). Four trees per plot were sampled in May, with 8 trees per plot sampled in June, July, and August. Cards were cut to 26×52 mm. Cards were placed on both sides of the tree respective to the row at three different vertical locations: ‘low’, .7 m above ground; ‘medium’, 1.4 m; and ‘high’, 2.1 m. Heights were as close as the branching of the canopy would allow, within approximately .15 m of the target height. Cards were then clipped in pairs onto the adaxial and abaxial leaf surfaces (face up, face down) with binder clips to leaves to simulate foliar exposure. Cards were collected after drying in situ and affixed to a sheet of paper pre-labeled with date, row side, row number, plot number, collection height, card orientation and treatment. Coverage evaluations were done on days with <80% relative humidity in the afternoon and similar ambient conditions. Once cards were collected they were stored in a sealed container with silicon desiccant to prevent any issues with water vapor reacting with the coating.

A flatbed scanner was then used to digitize the cards and associated identification for further analysis at a 1200dpi resolution. ImageJ software (Rasband, 1997) using the plugin DepositScan (Zhu et al., 2011) was used to automatically calculate the percentage card coverage. However, DepositScan occasionally had difficulties recognizing droplet coverage on cards with <5% coverage and >95% coverage and returned inaccurate coverage values in those ranges. For these cards a manual threshold slider was used to differentiate the droplets from the background.

Deposition

Deposition was computed by determining the quantity of Keyacid Tartrazine (Keystone Corp., Chicago, IL), a food grade yellow dye, recovered from 90mm filter paper and leaf surfaces. Filter papers were used as artificial targets instead of leaves during the May sampling date since leaf surface area was too small. A 96 well plate Biotek® Synergy™ HT microplate reader was used to ascertain the absorbance of samples at 435nm. A standard curve was generated to determine the relationship between concentration and absorbance, as well as the minimum and maximum absorbance values. Serial dilutions were made from a stock solution of 1 g L^{-1} in concentrations of 1 g L^{-1}, .5 g L^{-1}, .1 g L^{-1}, .075g L^{-1}, .05 g L^{-1}, .025g L^{-1}, .01 g L^{-1}, .0075g L^{-1}, .005 g L^{-1}, .0025g L^{-1}, and .001 g L^{-1}. The stock solution was used to make dilutions to .5, .1, .05, .01, .005 and .001 g, with each successive dilution made from the previous concentration, while the .075, .025, .0075 and .0025 g L^{-1} samples were made from the previous concentration but were not used to make the next dilution. Five 200 µL samples of each concentration were transferred to a 96 well plate with five water blanks, and an absorbance reading at 435 nm was taken. Data was then transferred to excel for organization and SAS for analysis with PROC REG. The magnitude of the absorbance for the 1 g L^{-1} and .5 g $L-^{1}$ samples was too high for the microplate reader, but absorption values for concentrations between .1 g L^{-1} and .001 g L^{-1} showed a linear relationship with an average R^2 value of .996. Two replications with 5 subsamples of each concentration were used to create a linear regression, which was then used to produce an equation to calculate unknown concentrations from known absorbance values.

Sprays were made at a rate of 654.8 L ha^{-1} with a mix of Tartrazine and the nonionic surfactant Latron-B 1956, with the Tartrazine mixed in a concentration of 1 g L^{-1} and surfactant concentration of 1 ml L^{-1}. After spray applications, three leaves were collected from each sampling location once the application had dried. Leaf samples were collected from the same terminal where the WSPs were located, and stored in Ziploc bags for residue analysis. A single leaf was then placed in a 50 mL centrifuge tube (Denville Scientific Inc., Holliston, Maryland, USA), filled with 25 mL of water, and inverted repeatedly for 20 seconds. The leaf was then removed and placed in a leaf press with identifying information. Leaves were pressed and dried, and then a LI-COR 3100 Area Meter (LI-COR Biosciences, Lincoln, Nebraska, USA) was used to determine the surface area. Two 200 µL samples were taken from each 25 mL sample washed from the leaves, and pipetted into the 96 well plate. Absorbance values were averaged and then used to calculate the concentration and therefore mass of tartrazine in each sample washed from the leaves. Total tartrazine mass was combined with the leaf surface area and deposition was expressed as $\mu g/cm^2$.

Pest Management Applications and Monitoring

Pathogens and arthropod pests were managed throughout the spring and summer of 2016 with agrochemicals applied to the .09 ha plots through the solid set canopy delivery system and air blast. Buffer rows and buffer gaps between plots were not treated. Each plot received the same treatment on the same day, with SSCDS plots sprayed first, and then air blast plots sprayed with the remaining tank mix. Plant protectants were applied in the same fashion as sprays for coverage and deposition quantification. The first four fungicide sprays of the year (before April 29th) were only applied through the air blast, as the SSCDS was not yet de-winterized and running. Copper Hydroxide was applied at 6.75 kg ha^{-1} on March 30th, Mancozeb (Penncozeb, United Phosphorous, King of Prussia, Pennsylvania) at 3.35 kg ha^{-1} on April 15th, Captan (Captan 80 WDG, Arysta LifeScience, Cary, North Carolina) at 3.75 kg ha^{-1} on April 20th, and Manzoceb and Tebuconazole (Indar, Dow AgroSciences, Indianapolis, Indiana) at 4.9 and 5.3 kg ha^{-1} on April 25th. Agrochemicals applied through both the system and the air blast for the rest of the season are summarized in Table 3.2.

Insect and pathogen damage were recorded in the mid-season and pre-harvest intervals, on July 6th and August 26th respectively. Assessments were made on the sixteen trees in each plot. To rate foliar apple scab (*Venturia inaequalis*, Cooke) severity, 20 terminals and 20 clusters were checked per tree, with half of the observations coming from each side of the row. Clusters and terminals were checked at all heights throughout the tree, and randomly selected. To estimate the abundance of fruit feeding pests and rate apple scab, 20 fruit on each tree from both sides of the row and throughout the height of the tree were randomly selected and examined.

Scab damage was assessed as a percentage, approximated as either 0, 2, 5, 10, 20, 40, 60, 80, 90, 95, 98, or 100%. Observers were trained to recognize the olive to dark brown colored lesions on the surface of the leaf. Damage from Obliquebanded Leafroller (*Choristoneura rosaceana*, Harris) was recorded from feeding in rolled leaves or leaf rolls or structures webbed upon fruit. Stinkbug (Pentatomidae) feeding injury assessed based on the distinctive conical pits and puncture marks the stylet produces. Codling moth (*Cydia pomonella*, L.)and Oriental fruit moth (*Grapholita molesta*, Busck) damage to fruit were recorded based on stings and larval entry tunnels and grouped as internally feeding pests. Apples that displayed entry tunnels were returned to the lab and dissected to determine which species had caused the damage, but that level of identification was not discerned in the field. Plum curculio (*Conotrachelus nenuphar*, Herbst) counts were based on the pits left from feeding and the crescent shaped oviposition scar left on the skin of the apple following oviposition.

Table 3.2 Formulations, rates, and type of chemical applications made through both systems.

Date	Product	Rate	Type
4/29/2016	Sivanto Prime L	12oz/acre	Insecticide
	Manzate Pro-Stik	6 lbs/acre	Fungicide
	Aprovia	4.27oz/acre	Fungicide
5/2/2016	Tartrazine	9.35oz/acre	Dye
	Latron-B 1956	1.25oz/100gal	Surfactant
5/6/2016	Manzate Pro-Stik	4 lbs/acre	Insecticide
	Inspire Super	8.5oz/acre	Fungicide
5/13/2016	Aprovia	4.27oz/acre	Fungicide
	Roper	4 lbs/acre	Fungicide
	Kasumin	64oz/acre	Bactericide
5/19/2016	Assail	6oz/acre	Insecticide
	Rally	5oz/acre	Fungicide
5/25/2016	Luna Sensation	5 oz/acre	Fungicide
	Belay	6 oz/acre	Insecticide
6/6/2016	Ziram	4 lbs/acre	Fungicide
	Rally	5oz/acre	Fungicide
	Reaper	10oz/acre	Insecticide
	Prey	6oz/acre	Insecticide
	Belay	6oz/acre	Insecticide
	Belt	4oz/acre	Insecticide
	Damoil	1gal/100gal	Insecticide
6/8/2016	Tartrazine	9.35oz/acre	Dye
	Latron-B 1956	1.25oz/100gal	Surfactant
6/14/2016	Ziram	4lbs/acre	Fungicide
	Assail	6.4oz/acre	Insecticide
6/29/2016	Flint	2oz/acre	Fungicide
	Captan Gold	5.0lb/acre	Fungicide
	Altacor	4oz/acre	Insecticide
7/8/2016	Movento	9 oz/acre	Insecticide
7/12/2016	Tartrazine	9.35oz/acre	Dye
	Latron-B 1956	1o.25z/100gal	Surfactant
7/19/2016	Nealta	13.7oz/acre	Miticide
	Captan Gold	3lb/acre	Fungicide
7/22/2016	Indar	6oz/acre	Fungicide
8/1/2016	Delegate	4.4oz/acre	Insecticide
	Flint	2oz/acre	Fungicide
8/8/2016	Tartrazine	9.35oz/acre	Dye
	Latron-B 1956	1.25oz/100gal	Surfactant
8/15/2016	Delegate	4.4oz/acre	Insecticide
	Flint	2oz/acre	Fungicide

There was no replicated untreated control portion in the experimental orchard, but 16 trees in four rows located in a separate high-density apple orchard .5 kilometers away were assessed for the same insect and fungal damage. Trees had not been treated over the course of the season and served as a check to determine whether arthropods and pathogens were present and active in the area.

Statistical Analysis

Adaxial and abaxial coverage data were arcsin transformed to meet assumptions of normality and to reduce heteroscedasticity, and analyzed separately. Both data sets still displayed significant heteroscedasticity for the factor 'Treatment' when tested with a Levene's test so variances were grouped by treatment and analysis proceeded with an unequal variance model. The main fixed effects were date, treatment, and height, with plot as a random factor. Data were fit to a repeated measures split-plot ANOVA model in SAS 9.4 PROC MIXED (SAS Institute Inc., Cary, NC, USA) as each measurement at each date was taken from the same tree and height. Sample height was considered the subplot factor. Data from either side of the tree were not pooled, to prevent artificial variance reduction. There was a single missing data point in the adaxial coverage data set, and a pair in the abaxial coverage measurement. Residuals for each factor were and combination of factors were visually inspected with boxplots, residual vs. predicted value, and residual vs. quantile plots. Multiple comparisons for main effects and interactions were performed using the LSMEANS statement adjusted with Tukey's HSD and Tukey-Kramer test. Arcsin transformed least square means and standard errors were backtransformed with the procedure described by Erik Jørgensen and Asger Roer Pedersen (Jørgensen and Pederson, 1998).

Coefficients of variation were calculated for each height of each plot for the three balanced dates as an index of dispersion to assess differences in variability displayed by the coverage profile of each spray type. Coefficients of variation were assessed for normality before being analyzed with a repeated measures ANOVA as well. Adaxial coefficients of variation showed no significant differences in variances with a Levene's test, and met assumptions of normality, but abaxial coefficients of variation were square root transformed to meet normality assumptions.

Deposition was analyzed with an identical model to the abaxial and adaxial data, but with variances grouped by date, treatment, and height in order to achieve the best model fit. For deposition data, 5 outliers were removed that were skewing means, with the cutoff at 5.00 ug/cm^2. Four outliers came from SSCDS plots, and one was from airblast treated plots. Coefficients of variation were also computed for deposition and analyzed as before. Pest management data was non-normal and could not be transformed to meet normality or homoscedasticity assumptions. Counts of pest damage from each treated plot were compared between treatments with Wilcoxon rank sum tests using SAS 9.4 NPAR1WAY.

Results

Adaxial Coverage

A repeated measures ANOVA on data from the three months with balanced comparisons (June, July, and August) showed a significant difference in adaxial (upper surface) coverage attributed to the main effect of treatment ($F_{1,6}$=15.92, p=.0072), and the interaction of treatment and height fixed effect terms ($F_{2,12}$=5.66, p=.0186). Air blast treated plots had significantly higher coverage overall, and significantly higher coverage at the highest height on each date (Figure 3.4). Date was also a significant fixed effect ($F_{2,44}$=9.13, p=.0005). Multiple comparisons by month using

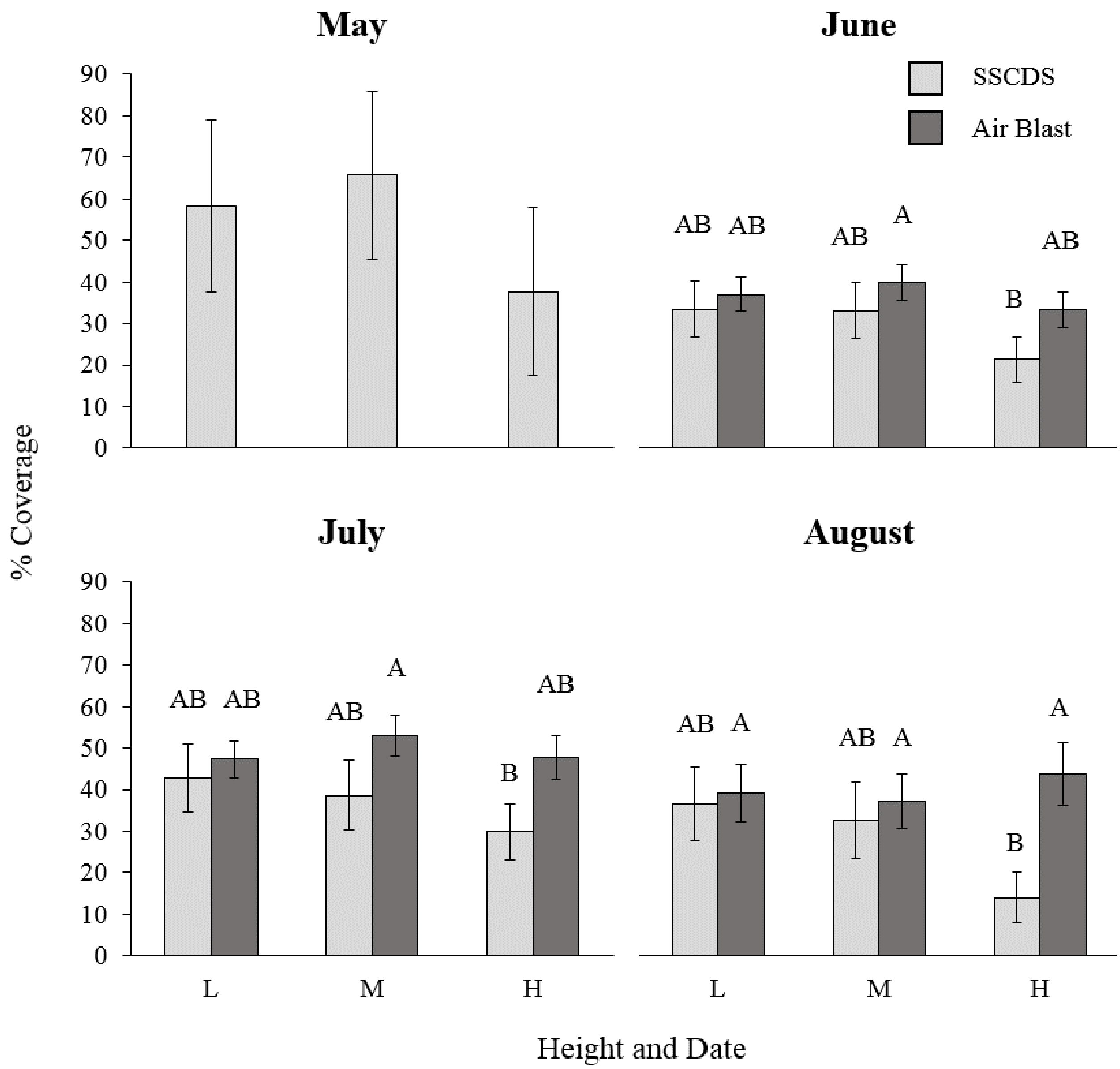


Figure 3.4 Least square means of the percent adaxial coverage. Means shown for each of the sampled dates (5/2/16, 6/8/16, 7/12/16, and 8/8/16) and heights (L=.7m, M=1.4m, H=2.1m). Error bars indicate (Tukey-Kramer) 95% confidence intervals, and different letters within a month indicate significant differences between treatments at each height. No significant differences were detected in May.

the Tukey-Kramer adjustment show that air blast treated plots displayed significantly higher coverage in one month, August ($t_{\alpha=.05,44}$= 3.20, adj. p=.0289), while in June and July they were not significantly different at the alpha=.05 level ($t_{\alpha=.05,44}$= 1.87, adj. p=.4359; $t_{\alpha=.05,44}$= 2.89, adj. p=.0625) (Figure 3.4).

Comparisons between the two treatments at the same height showed a significant difference with greater air blast coverage on the highest sampled leaves ($t_{\alpha=.05,12}$= 5.07, adj. p=.0029), but cards at the lower and middle heights did not show any significant differences ($t_{\alpha=.05,12}$= .85, adj. p=.9517; $t_{\alpha=.05,12}$= 2.03, adj. p=.3816). Different heights in air blast treated plots were not significantly different from each other: high and low ($t_{\alpha=.05,12}$= .12, adj. p=.9046), high and middle ($t_{\alpha=.05,12}$= -0.59 , adj. p=.9896), and middle and low ($t_{\alpha=.05,12}$= -0.71, adj. p=.9764). In comparison, different heights in SSCDS treated plots showed significant differences at the high and low heights ($t_{\alpha=.05,12}$= -3.83, adj. p=.0226), but not at the high and middle ($t_{\alpha=.05,12}$= -3.21 , adj. p=.0641) or middle and low ($t_{\alpha=.05,12}$= 0.62, adj. p=.9973).

Coefficients of variation were calculated for each plot at each of the three balanced dates, and showed treatment as a significant effect ($F_{2,6}$=127.84, p<.0001), as well as height ($F_{2,12}$=10.36, p=.0024), and date ($F_{2,36}$=8.28, p=.0011). Coefficient of variation least square means were .5127 for the air blast and .9889 for the SSCDS, with a shared standard error of ±.029. Comparisons between least square means of coefficients of variation using Tukey's adjustment were significantly different from each other in each of the three months, with a higher SSCDS σ^2/μ at each date: June ($t_{\alpha=.05,36}$= -3.38, adj. p=.0201), July ($t_{\alpha=.05,36}$= -5.86, adj. p<.0001), and August ($t_{\alpha=.05,12}$= -5.41, adj. p<.0001). Neither of the treatments displayed any significant differences with themselves across months- except for the SSCDS- where a significant difference occurred in σ/μ between July and August ($t_{\alpha=.05,36}$= -3.51, adj. p<.0144) (Table 3.3).

Table 3.3 Coefficient of Variation of adaxial coverage for each date and height. Least square mean of each treatment, height, and date combination on the left and least square mean of the overall date and treatment combination to the right.

		June		July		August	
Air Blast	L	0.493		0.381		0.560	
	M	0.502	0.529	0.419	0.434	0.536	0.5744
	H	0.593		0.503		0.627	
SSCDS	L	0.830		0.816		0.883	
	M	0.876	0.9397	0.902	0.908	1.014	1.261
	H	1.112		0.984		1.481	

Abaxial Coverage

A repeated measures ANOVA on data from the three months with balanced comparisons (June, July, and August) showed a significant difference in abaxial (lower surface) coverage by treatment ($F_{1,6}$=200.72, p<.0001) with significantly higher coverage from the air blast. The interaction of treatment and height fixed effect terms ($F_{2,12}$=12.88, p=.0010) was also significant. Date was also a significant fixed effect ($F_{2,44}$=14.6, p<.0001). Multiple comparisons by month using the Tukey-Kramer adjustment show that air blast treated plots displayed significantly higher coverage in all three months: June ($t_{\alpha=.05,44}$= 7.86, adj. p<.0001), July ($t_{\alpha=.05,44}$= 10.18, adj. p<.0001), and August ($t_{\alpha=.05,44}$= 10.48, adj. p<.0001) (Figure 3.6).

Comparisons between the two treatments at the same height showed a significant difference between the coverage at all three heights, with higher coverage from the air blast at each point: high ($t_{\alpha=.05,12}$= 12.57, adj. p<.0001), middle ($t_{\alpha=.05,12}$= 6.07, adj. p<.0001), and low ($t_{\alpha=.05,12}$= 9.89, adj. p<.0001). Different heights in air blast treated plots were not significantly different from each other: high and low ($t_{\alpha=.05,12}$= 3.1, adj. p=.0774), high and middle ($t_{\alpha=.05,12}$= 1.82 , adj. p=.4899), and middle and low ($t_{\alpha=.05,12}$= 1.27, adj. p=.7942. In comparison, different

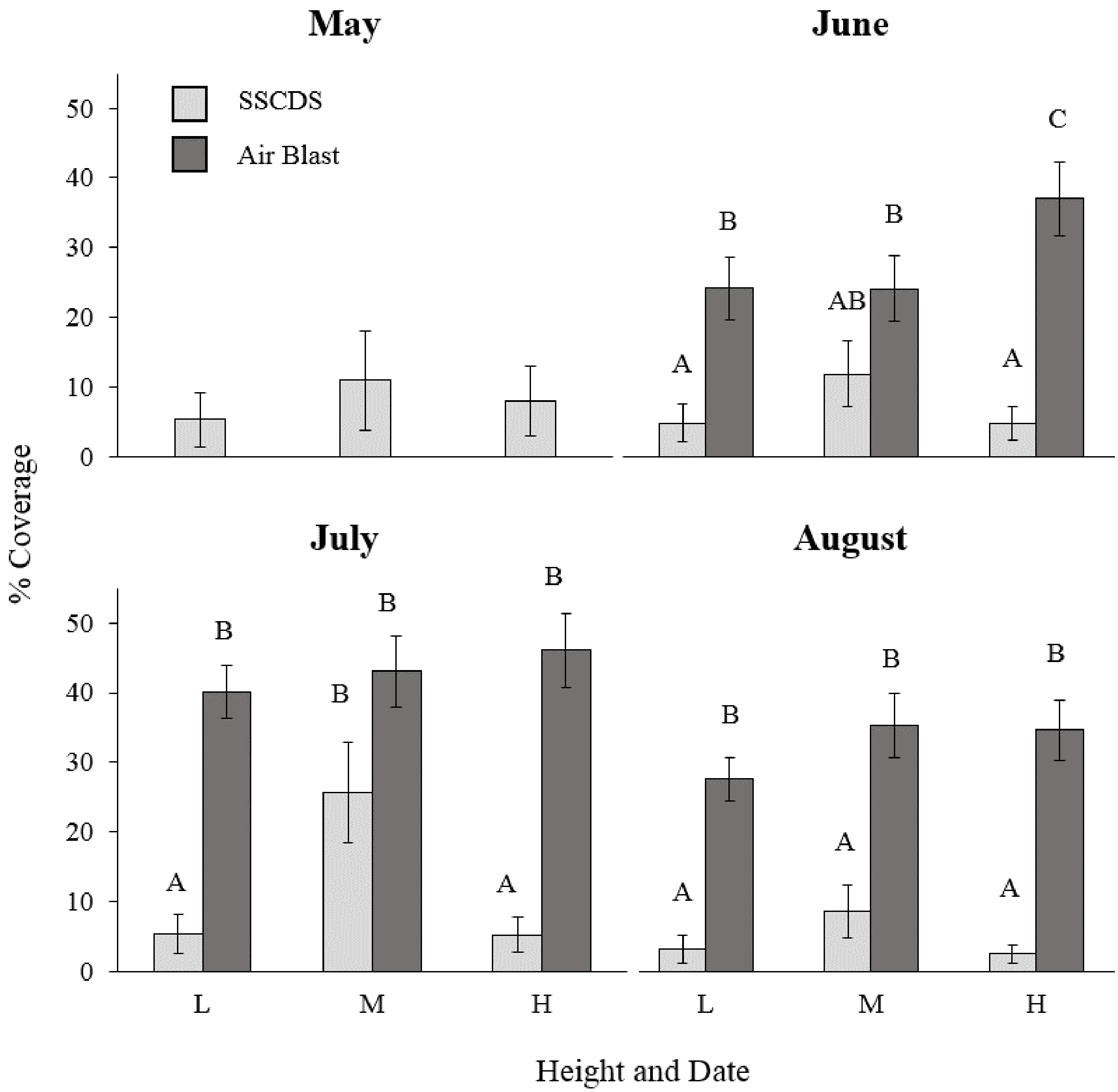


Figure 3.5 Least square means of the percent abaxial coverage. Means shown for each of the sampled dates (5/2/16, 6/8/16, 7/12/16, and 8/8/16) and heights (L=.7m, M=1.4m, H=2.1m). Error bars indicate adjusted (Tukey-Kramer) 95% confidence intervals, and different letters within a month indicate significant differences between treatments at each height. No significant differences were detected in May.

heights in SSCDS treated plots showed significant differences at the middle and low heights ($t_{\alpha=.05,12}$= -4.99, adj. p=.0048) as well as the middle and high ($t_{\alpha=.05,12}$= -4.99, adj. p=.0033), but not between the high and low ($t_{\alpha=.05,12}$= -0.23, adj. p=.9999) (Figure 3.5).

Coefficients of variation were again calculated for each plot at each of the three balanced dates for abaxial coverage. The fixed effect of treatment was significant ($F_{2,6}$=197.67, p<.0001), with higher coefficients of variation for the SSCDS treatments. Interaction of date and treatment and treatment and height were also significant ($F_{2,36}$=5.45, p=.0085; $F_{2,12}$=16.12, p=.0004). Back-transformed σ/μ least square means were 0.563 for the air blast and 1.345 for the SSCDS. Comparisons between least square means of the coefficient of variation using Tukey's adjustment were significantly different from each other in each of the three months, with a higher SSCDS σ/μ at each date: June ($t_{\alpha=.05,36}$= -8.97, adj. p<.0001), July ($t_{\alpha=.05,36}$= -11.06, adj. p<.0001), and August ($t_{\alpha=.05,36}$= -12.58, adj. p<.0001). SSCDS σ/μ displayed significant differences between July and August ($t_{\alpha=.05,36}$= -4.57, adj. p=.0007) as well as June and August ($t_{\alpha=.05,36}$= -4.68, adj. p=.0005), while air blast plots did not. (Table 3.4)

Table 3.4 Coefficient of Variation of abaxial coverage for each date and height. Least square mean of each treatment, height, and date combination on the left and least square mean of the overall date and treatment combination to the right.

		June		July		August	
Air Blast	L	0.598	0.619	0.346	0.458	0.566	0.6201
	M	0.712		0.521		0.655	
	H	0.551		0.517		0.642	
SSCDS	L	1.924	1.631	2.082	1.644	2.448	2.179
	M	1.394		1.142		1.915	
	H	1.587		1.782		2.192	

Deposition

Analysis using data from the three months with balanced comparisons (June, July, and August) showed significantly higher chemical deposition in SSCDS treated plots than in air blast treated plots ($F_{1,6}$=15.84, p=.0073). The interaction of treatment and height fixed effect terms was also significant ($F_{2,12}$=7.41, p=.0080). Date was also a significant fixed effect ($F_{2,36}$=16.41, p<.0001). Multiple comparisons by month using the Tukey-Kramer adjustment show that SSCDS treated plots displayed significantly higher deposition in all three months: June ($t_{\alpha=.05,36}$= -3.09, adj. p=.0413), July ($t_{\alpha=.05,36}$= -3.69, adj. p=.0088), and August ($t_{\alpha=.05,36}$= -3.10, adj. p=.0402) (Figure 3.6).

Comparisons between treatments at the same height showed no significant differences between the deposition on the highest sampled leaves ($t_{\alpha=.05,12}$= -1.16, adj. p=.8450), but leaves at the lower and middle heights showed significantly higher deposition from the SSCDS ($t_{\alpha=.05,12}$= -4.58, adj. p=.0064; $t_{\alpha=.05,12}$= -4.08, adj. p=.0149). Different heights in air blast treated plots were not significantly different from each other: high and low ($t_{\alpha=.05,12}$= 2.40, adj. p=.2296), high and middle ($t_{\alpha=.05,12}$= 1.23, adj. p=.8132), and middle and low ($t_{\alpha=.05,12}$= -1.21, adj. p=.8221). Differences in deposition due to height in SSCDS treated plots were also non-significant: high and low ($t_{\alpha=.05,12}$= -2.68, adj. p=.1519), high and middle ($t_{\alpha=.05,12}$= -281, adj. p=.1239), and middle and low ($t_{\alpha=.05,12}$= -.18, adj. p=.8600).

Coefficients of variation (σ/μ) calculated for each height in each plot for the three dates showed treatment as a significant effect ($F_{2,6}$=28.99, p=.0017), as well as date ($F_{2,36}$=7.84, p=.0015), but not height ($F_{2,12}$=2.16, p=.1579). There were no significant interactions. Coefficient of variation least square means were .7185±.028 for the air blast and .9343±.028 for the SSCDS. Comparisons between least square means of the coefficient of variation using

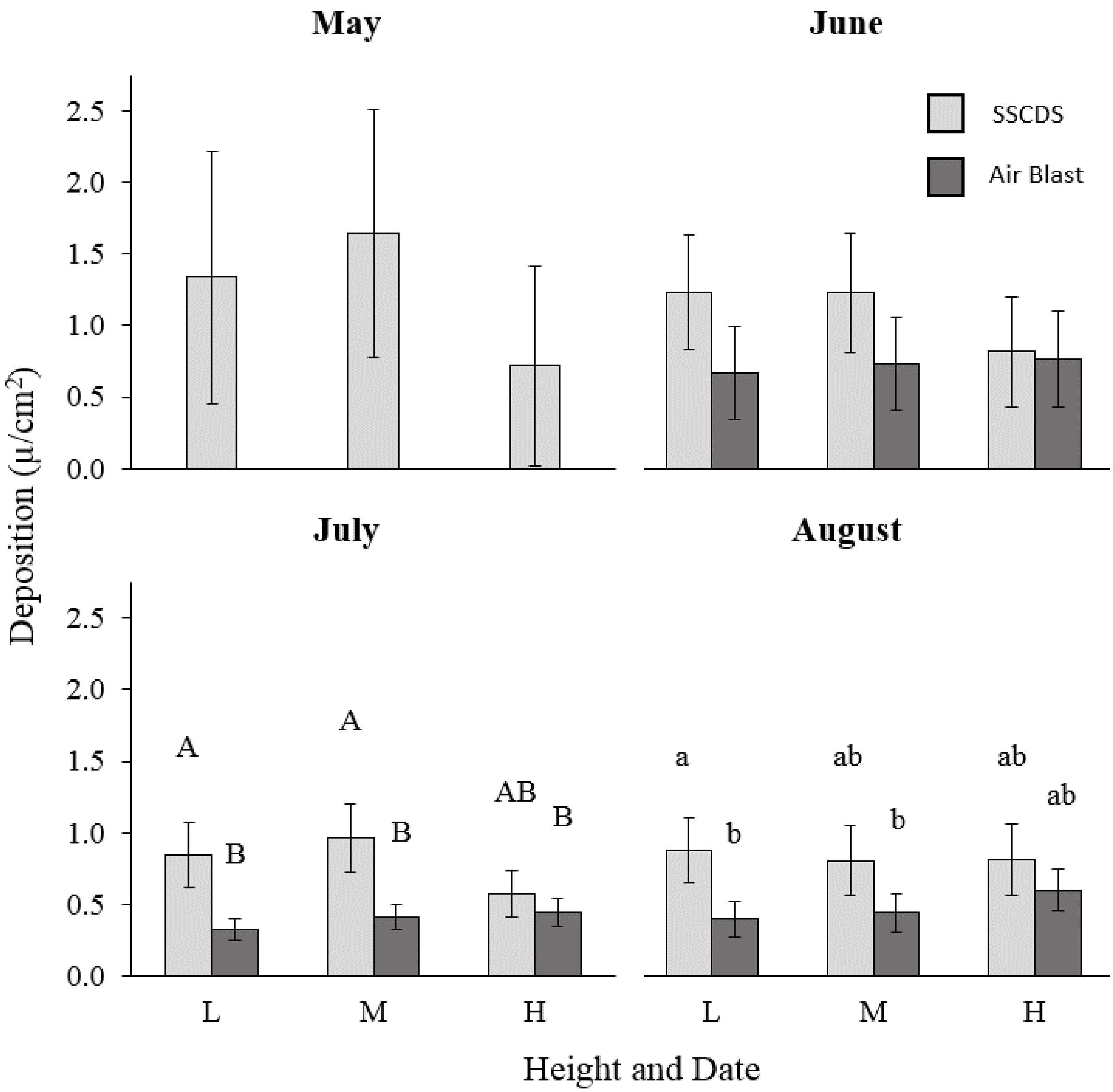


Figure 3.6 Least square means of deposition of tartrazine dye in μ/cm². Means shown for each of the sampled dates (5/2/16, 6/8/16, 7/12/16, and 8/8/16) and heights (L=.7m, M=1.4m, H=2.1m). Error bars indicate adjusted (Tukey-Kramer) 95% confidence intervals, and different letters within a month indicate significant differences between treatments at each height. No significant differences were detected in May and June. Note the difference in scale between the top and bottom pairs of graphs

Tukey's adjustment were significantly different from each other in June ($t_{\alpha=.05,44}$= -3.79, adj. p=.0068) and August ($t_{\alpha=.05,44}$= -3.26, adj. p=.0271), with a higher SSCDS σ/μ, but not in July ($t_{\alpha=.05,44}$= -2.28, adj. p=.2299). (Table 3.5)

Table 3.5 Coefficient of Variation of deposition for each date and height. Least square mean of each treatment, height, and date combination on the left and least square mean of the overall date and treatment combination to the right.

		June		**July**		**August**	
Air Blast	L	0.186		0.186		0.300	
	M	0.204	0.586	0.236	0.777	0.282	0.792
	H	0.327		0.290		0.303	
SSCDS	L	0.639		0.701		0.704	
	M	0.893	0.8494	0.660	0.935	0.833	1.02
	H	0.729		0.629		0.976	

A separate ANOVA model fitted to just SSCDS deposition data from all four dates (May, June, July, and August) resulted in a significant F-test for the main effect of date ($F_{3,27}$=4.91, p=.0075). Deposition in July and August were both significantly lower than the deposition in June ($t_{\alpha=.05,27}$= -3.28, adj. p=.0144; $t_{\alpha=.05,27}$= -2.78, adj. p=.0454), but other date combinations did not display significant differences. Another ANOVA model was fitted to air blast deposition from June, July, and August, and showed the same pattern, with deposition in July and August significantly lower than the deposition in June ($t_{\alpha=.05,18}$= -5.45, adj. p<.0001; $t_{\alpha=.05,18}$= -3.84, adj. p=.0033), but July and August were not significantly different from each other ($t_{\alpha=.05,18}$= -1.51, adj. p=.3087).

Pest Management

Apple scab damage evaluations did not yield any scores higher than 5% on leaves, terminals, or fruit in both treatments. A single sign of Leafroller damage was observed in air blast plots. Collected fruit with entries and frass did not yield any live larvae. Wilcoxon rank sum tests between air blast and SSCDS plots did not show any significant differences (Table 3.6) except for the incidence of apple scab on clusters. No apple scab was found on fruit in air blast treated plots, while two incidences of 5% scab damage and 12 incidences of 2% scab damage were found on SSCDS treated fruit. Proportions of damaged fruit and leaves are displayed in Figures 3.7 and 3.8, along with an untreated comparison.

Table 3.6 Results of four exact Wilcoxon rank sum tests for each category of damage. 'Internal' refers to internally feeding lepidopteran damage from stings or entries, and 'external' refers to damage from Plum Curculio and Pentatomidae. 'Terminal' and 'cluster' refer to apple scab damage on those portions of the plant. Significance was determined at the alpha=.05 level.

Damage Type		Z-Value	Pr. < Z
Arthropod	Internal	-1.080	0.140
	External	1.527	0.063
Apple Scab	Terminal	.540	0.295
	Cluster	-.588	0.278

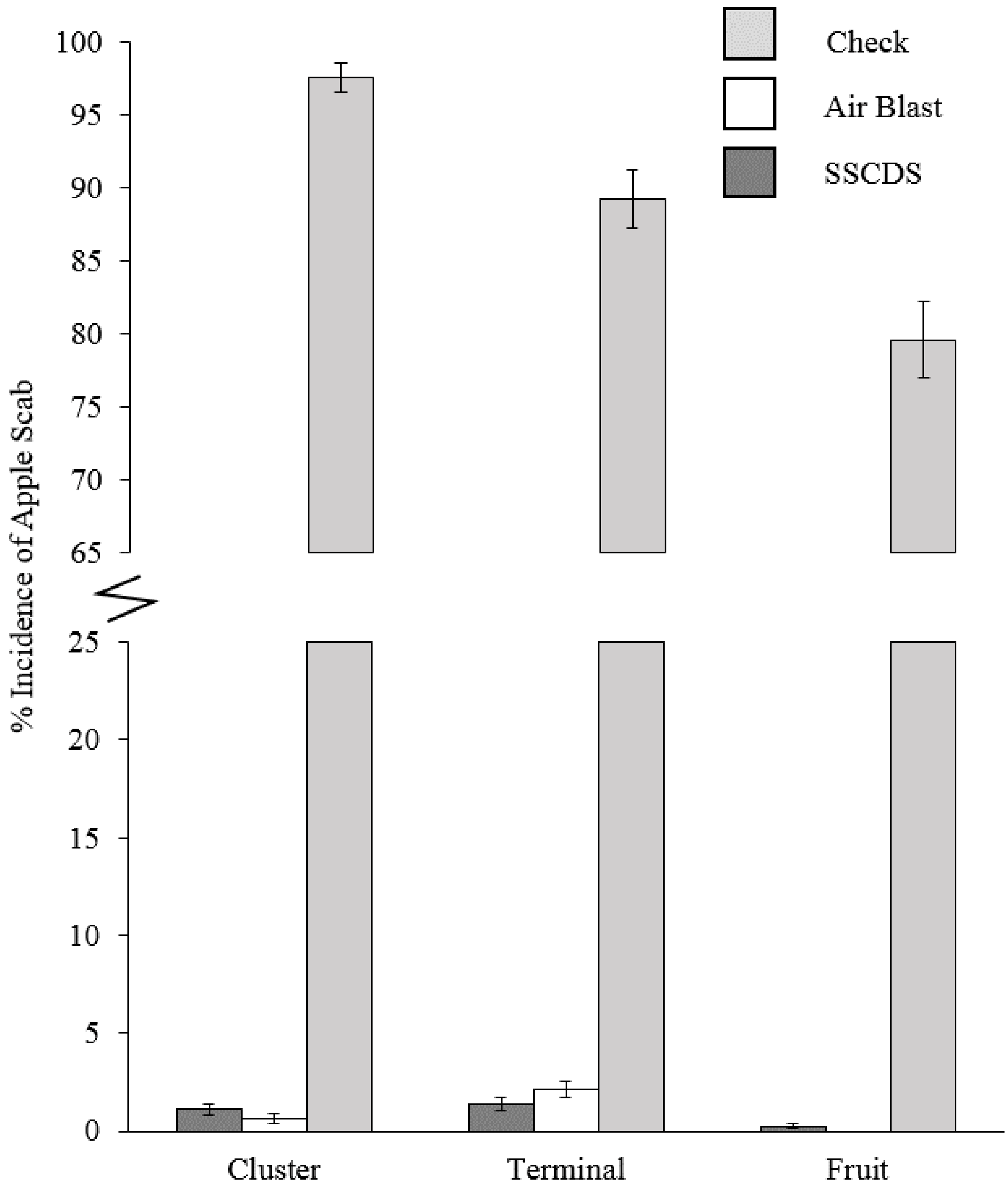


Figure 3.7 Observed percent incidence of apple scab in each tissue type. Mean incidence shown from the air blast and SSCDS treated plots, with a comparison check from a nearby untreated orchard. Error bars indicate standard error of the proportion.

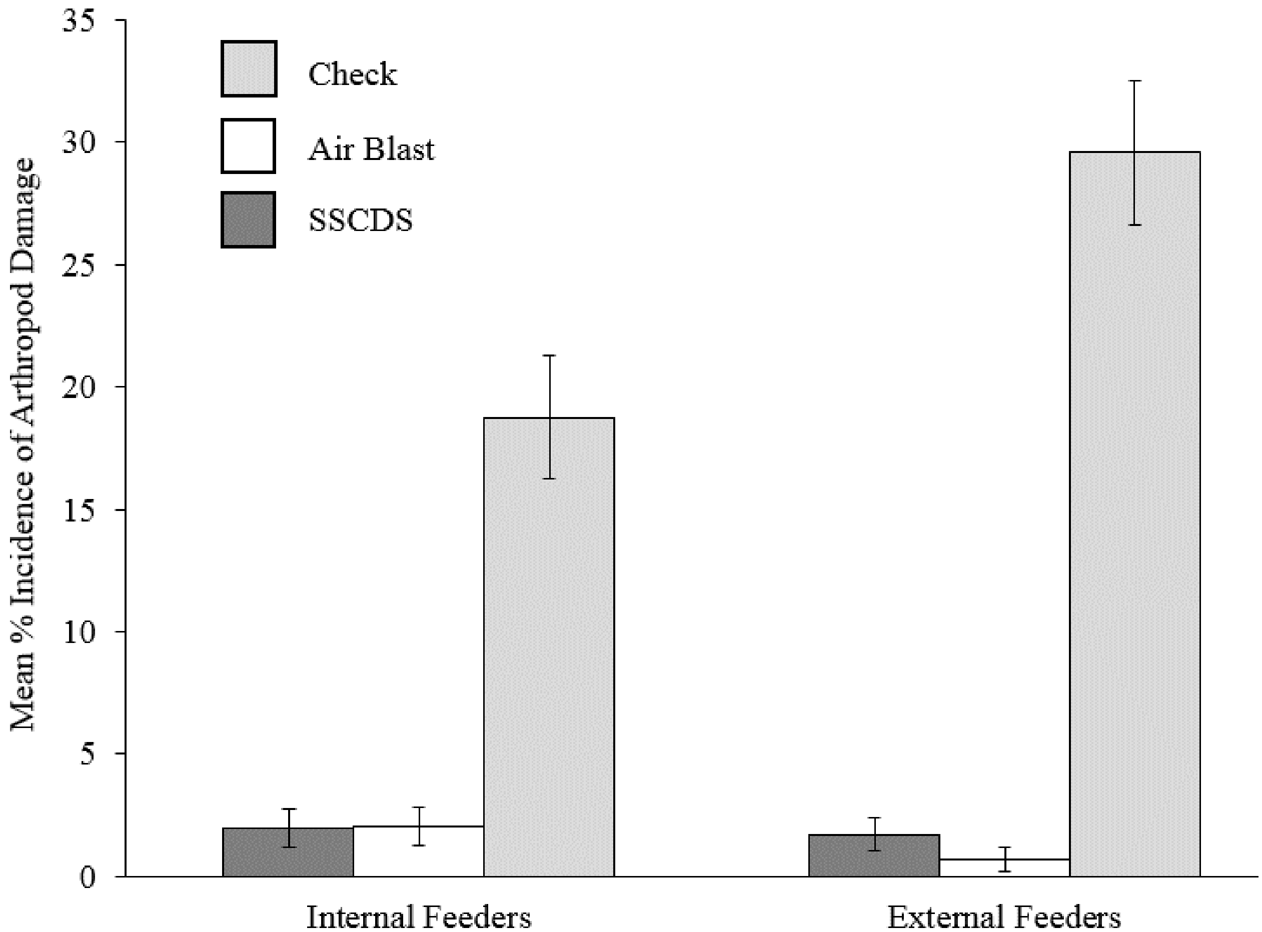


Figure 3.8 Mean percent incidence of arthropod damage. Means shown from the air blast and SSCDS treated plots, with a comparison check from a nearby untreated orchard. Error bars indicate standard error of the proportion.

Discussion

Coverage evaluations collected in this experiment showed that SSCDS provides comparable levels of coverage on the adaxial leaf surface to an air blast (Figure 3.4). However, SSCDS coverage on the adaxial surface is far higher than the SSCDS coverage on the abaxial surface, which confirms previous observations (Sharda et al., 2015; Verpont et al. 2015, Niemann and Whiting, 2016). Additionally, coverage on the underside of leaf surfaces is far lower when sprayed with the SSCDS than the coverage obtained with air blast spraying, and significantly lower in almost all cases (Figure 3.5). Despite the low abaxial coverage, SSCDS sprayed plots exhibited equal or greater levels of chemical deposition on sampled leaves (Figure 3.6), which implies less chemical was lost from the SSCDS sprays in the form of drift. Both systems demonstrated near identical levels of pest control, which is ultimately the most important characteristic of any spray application.

The adaxial coverage measurements only showed an overall significant difference between the two spray types in August, with similar levels of coverage in June and July. Most major sprays in Michigan are applied between mid-April and July, with only three sprays in the test orchard in August (Table 3.2). This suggests that despite the lower adaxial coverage in August, the SSCDS can provide similar levels of coverage in the major portion of the growing season. However, SSCDS adaxial coverage was significantly lower at the highest sampled height (2.1m) than the coverage it provided in the lower and middle portions of the canopy, and significantly lower than the adaxial coverage from an air blast at the same height. This sampling height was approximately 2/3 of the height of typical high density apple trees (2.5-3.3m), and just under the height the highest set of sprinklers sprayed from. Coverage there could potentially be improved by changes in the height, arrangement, or number of the highest set of emitters to attain levels of coverage seen in the lower and middle portion of the canopy. Mean adaxial coverage was still well within the recommended range of coverage found in the literature, from 15% (Deaveau, 2015) to 30%(Holownicki et al., 2002), falling within or above this range at all heights and dates.

Coefficients of variation of the adaxial coverage were around two-fold greater in SSCDS sprayed plots, indicating more heterogeneity in coverage than the air blast. The magnitude of this difference was again the most severe at the highest sampled height, where coverage was the lowest, indicating that it was not only lower but much more variable. Coefficients of variation were significantly higher in the SSCDS treatment at each date, but were highest overall in August, when the SSCDS also showed significantly lower coverage than the air blast. This could be attributed to the full canopy development and foliar growth that occurs throughout the summer, blocking spray from the fixed emitters and resulting in lower and uneven coverage.

Abaxial coverage was significantly lower at every height and on every date overall when compared to the air blast sprayer. It was lowest in the bottom portion of the canopy and the highest portion of the canopy. This is likely because the solid set lacks the moving air front from an axial fan, which both lifts and turns leaves (Fox et al., 2008). This action spreads fine droplets within a turbulent airstream so they either intercept the underside of leaves or are sprayed directly onto the upturned abaxial surface. The droplets delivered through the fixed spray system are far less likely to reach the underside of the leaf unless it is located near the emitter and received direct spray or natural air movement carries droplets through the canopy. Additionally, SSCDS abaxial coverage exhibited significantly higher coefficients of variation than the air blast (Table 3.4). In some cases the CoV was nearly four times greater than the corresponding CoV seen in air blast treated plots. This was greater than the disparity between CoV’s in adaxial coverage as well, showing abaxial surfaces not only receive less coverage, but have far more variable coverage when treated by the SSCDS.

It is important to note that the heterogeneous coverage and deposition referred to here is at the macroscale level of the tree or plot, rather than on the scale of individual droplets. The SSCDS not only exhibits variable coverage at the plot level, but also has a characteristically coarser distribution of droplets intercepting the spray cards (Figure 3.9). The coarse coverage at the plot level and the droplet level are likely related to some degree, the large splatters or light dusting of droplets on cards lead to much more variable overall percent coverage. However, the plot level heterogeneity of coverage can also be attributed to the static nature of the sprinklers.

Coverage variability on both surfaces and the low coverage on abaxial surfaces is likely caused by inherent properties of fixed spray systems. They may exhibit greater heterogeneity than air blasts since spray interception is much more likely to occur closer to where it is emitted from nozzles. Leaves further from the nozzle are less likely to intercept droplets, especially if they are distant vertically. Larger droplets are subject to gravity rather than air currents, and are pulled downward once they lose momentum (Spillman, 1984). This means adaxial surfaces receive a shower from above, but abaxial surfaces only receive droplets sprayed directly up onto them or the finest droplets that travel through the canopy environment on air currents. Literature has also been published on the local cooling effect provided by microsprinklers, which has been used for sunburn protection in apples (Niemann et al. 2016). Data collected in this orchard has shown a 2-3˚C drop in temperature when SSCDS sprinklers run (Owen-Smith, unpublished data). The cool air produced by this effect may also pull spray droplets downward as it sinks, contributing to the lower abaxial coverage and the lower coverage levels seen at the highest sampled portion of the canopy.

Deposition showed a very different profile than coverage- mean SSCDS deposition was greater at every height and date. Additionally, for the SSCDS the lower and middle tiers of the canopy had significantly higher deposition than those sprayed with the air blast. The difference in magnitude between the coefficient of variation from air blast and SSCDS treated plots was also lower than CoV differences in coverage measurements, but still significantly different in June and July. This suggests variability in deposition is still greater on SSCDS treated trees, but less so than the variability in SSCDS coverage. Higher levels of deposition suggest that more chemical was retained on the leaf surfaces in SSCDS plots, and less may have been lost to drift.

This phenomenon may be related to the issues air blast sprayers have with drift and loss of droplets to the orchard floor. Mass balance experiments in dwarf apple trees have shown 10-12% of the spray volume was lost to the ground, and 37-59% lost to the air (Holownicki, 2000), with 4-17% lost to the air and 10-22% lost to the ground in semi-dwarf trees. A separate study in Italian apple orchards has shown a loss of 37% of the spray to the ground and 7% to the air (Balsari et al, 2002). Without the moving front of air pushing small droplets above the canopy or into the ground, it is likely that more droplets intercept leaves and are deposited. If 40-50% of the air blast spray was lost to the ground and air, the difference between the mean deposition for each treatment would have been negligible if it had not been off target. This suggest that the SSCDS has the potential to reduce off target deposits, and may serve to reduce drift and soil contamination compared to an orchard air blast sprayer. The higher levels of deposition in SSCDS treatments suggest that less chemical is lost to the environment, and more is retained within the tree row, compared to sprays made with the air blast sprayer. Environmental conditions have a great deal of impact on the outcome of spray coverage and deposition. Average wind speed remained under 5 m s^{-1} for each of the spray events, but wind direction was different on each date. However, wind was always directed at an angle across the row, and never completely north/south (Table 3.1). This may have helped pull spray from row to row in the large simulated orchard blocks, and helped to increase SSCDS deposition. Visually, the fixed emitters throw little spray above the row compared to an air blast, and droplets from the air blast may have been caught by these winds and pulled away from the target environment. Alternately, deposition may be higher in the SSCDS because the coarser spray leads to higher levels of chemical contact in the sampled areas of the canopy, while the air blast has a more even deposition profile into the center and highest reaches of the canopy. This would lead to artificially high measures of SSCDS deposition; but orchard canopies are complex three dimensional environments and perhaps both explanations are factors.

Though the SSCDS may have had higher deposition, it was distributed less homogenously, which goes against conventional desirable spray characteristics. Typically, a uniform dispersion of droplets with similar levels of coverage and deposition throughout the canopy is considered ideal and coarse droplet patterns with variable coverage and deposition as something to be avoided as wasteful or inefficient (Wilkinson, 2000; Matthews, 2014). Coarse sprays may result in less optimal coverage than fine sprays, which can lead to worries among growers (Poulsen et al., 2012). However, Doruchowski et al. (2016) also found that air induction nozzles, known for their coarse droplets size and low drift potential, had a similar biological efficacy when compared to fine spray hollow cone nozzles.

Despite what might be considered inferior spray coverage, SSCDS plots exhibited near identical levels of disease and pest management to the air blast, with the only significant difference being a very low incidence of light (<5%) apple scab on fruit. This excellent control has also been observed with previous studies conducted by MSU (Owen-Smith, 2017), as well as other research groups. Part of this may be due to sub-detectable droplets that don't show up on water sensitive cards, but contribute to the overall higher levels of deposition seen on SSCDS treated leaves. Verpont et al. (2015) hypothesized these tiny droplets may still provide enough chemical residue for biological activity. Prior studies have also reported there is often minimal correlation between the observed deposition profile and the actual biological efficacy of the spray (Hislop, 1987). Wise et al. (2010) have also shown through bioassays that coverage and pest control do not necessarily correspond with each other. Pest management is the true goal of any application, and these results support the solid set canopy delivery system's potential as an alternative to air blast sprayers.

Despite its proven ability for pest management, there are still some concerns raised by heterogeneous coverage. Potential issues may arise with pests or pathogens that reside on the underside of the leaf-where the SSCDS has inferior coverage. Reservoirs of fungal bodies or spores may also avoid treatment if they are sheltered from treatment by dense foliage occluding spray. Viret et al. (2003) showed powdery mildew control in vines was best when both sides of the leaf received near equal treatment. Research has demonstrated that suitable coverage patterns are partly dependent on the mode of action of the compound (Wise et al. 2010). Fungicides or insecticides that have systemic or translaminar action, such as Aprovia (Benzovindiflypyr) or Assail (Acetamiprid) used in this experiment, should have little problem maintaining control since they are less reliant on even coverage. Arthropods such as European Red Mite (*Panonychus ulmi*, Koch) require near complete coverage for control (Leeper, 1980) since they lay eggs in crevices and spend much of their time on the underside of the leaf (Beers and Hoyt, 2007). The SSCDS could have issues conceivably controlling pests that have concealed life stages or aren't motile, that manage to avoid areas that receive spray. On the other hand, pests such as apple maggot (*Rhagoletis pomone*lla, Walsh) are very active and don't require high levels of coverage (Leeper, 1980). The efficacy of the SSCDS will be determined by the chemistry used, pest targeted, and environmental conditions; but a proper understanding of how the target and chemistry interact should overcome issues related to the uneven coverage and deposition.

Further work is needed to study how the solid set canopy delivery system handles the major pests in other growing environments, such as in the near desert conditions of Washington. Studies on the drift profile of SSCDS systems will be necessary to ensure they comply with governmental regulations, and confirm anecdotal evidence and visual inspection that suggests that it is less drift prone. Furthermore, different arrangements of microsprayers and styles of nozzles may improve abaxial coverage, increase coverage at the top of the trees, and reduce the heterogeneous coverage and deposition. Additional research in different crop profiles will help expand our knowledge of how fixed spray systems work in varying canopy sizes and densities, where it may be able to displace other types of spray technology as well.

CHAPTER FOUR – SYNTHESIS AND CONCLUSIONS

Improving the efficacy and targeting of spray applications in modern high density orchards is necessary to keep up with the change in horticultural practices. Axial fan tractor pulled air blasts have unresolved problems with off target deposition and drift (Pergher & Gubiani, 1995, Herrington et al., 1981; Cross, 1991; Doruchowski et al., 1997), since they were designed to spray trees that were much larger in stature. An optimized solid set canopy delivery system has the potential to retain more spray within the canopy, apply chemicals quickly and precisely, spray when the orchard is impassable by tractor, reduce operator exposure, and offer additional services such as evaporative cooling and frost protection. The goal of this this thesis was to quantify the spray coverage, deposition, and pest management of a solid set canopy delivery system and compare these characteristics with a standard orchard sprayer.

Appropriate coverage and deposition for the control of the target arthropod or pathogen is a major concern with any spray application. Without enough biologically active residue on the foliage or fruit crops may be damaged by the survivors of the initial spray (Wilkinson, 2000). The amount of chemical required for control is dependent on the target in question, the properties of the insecticide or fungicide, and the environmental conditions during the window that the chemical is active (Matthews, 2014). A search of the literature shows that there are very few published guidelines that recommend generally appropriate levels of spray coverage, likely because the required coverage can be so variable. However, spray coverage of 10-30% as measured by water sensitive paper is recommended according to Deaveau (2015) and Holownicki et al. (2002).

Results in 2013 and 2014 showed that the SSCDS had similar levels of coverage on the adaxial surface of the leaves as the air blast, but the abaxial surface had significantly lower coverage in 2013 (Figure 2.2). This trend was also evident in the 2016 portion of the study, with much higher levels of adaxial coverage at each height and date (Figure 3.4). Other research groups have confirmed this characteristic (Lang and Wise, 2010; Niemann and Whiting, 2014; Sharda et al., 2015; Verpont et al., 2015), which is a persistent feature of the SSCDS. Without the air agitation of an orchard sprayer, it may be difficult to improve the coverage on the underside of leaves, but changes in emitters as well as their placement and operating pressure may resolve this (Sharda et al., 2015). Low abaxial droplet interception is not an entirely new problem, coverage on crops sprayed by aircraft have showed low coverage (1%) in the lower portions of the canopy, as well as significant differences between the coverage on the adaxial and abaxial surfaces (Latheef et al., 2008).

Mean adaxial surface coverage from the second prototype SSCDS in 2016 ranged between 10-40%, right within the range recommended in the literature (Figure 3.4). Orchard sprayer coverage was between approximately 35-55%, which could be considered over spraying (Holownicki et al., 2002). However, the SSCDS also displayed far more heterogeneous levels of coverage, with some water sensitive cards in the canopy completely saturated and some with no coverage at all (Figure 3.9). This uneven coverage profile was observed on both the adaxial and abaxial leaf surfaces. Both the heterogeneous coverage and the low underside coverage can be attributed to the point source emission of spray rather than the moving front of air carrying droplets emitted by an air blast. Additionally. the abaxial surface of apple leaves are densely covered in trichomes, which impede droplet adhesion and might exacerbate the already low coverage (Wang et al., 2014). There are likely other factors that influence droplet interception, but canopy and droplet interactions are difficult to generalize since there are many environmental and physical properties that influence spray coverage.

Deposition in the 2016 season showed a very different trend than the coverage data would suggest, with the SSCDS exhibiting significantly higher deposition throughout the sampled regions of the canopy at each date (Figure 3.6). This runs counter to Niemann and Whiting's (2016) findings, where their SSCDS had significantly lower deposition. This may be because they estimated deposition based on droplet sizes and the number of impacts on water sensitive cards rather than with a tracer dye. It would be very difficult to accurately estimate the amount of active ingredient deposited on cards or leaves that were nearly saturated from droplet sizes, since they spread and overlap each other, sometimes to the point of runoff. Deposition also displayed the same spatial heterogeneity that was observed in coverage, and likely for the same reasons. It is interesting to note that the magnitude of the coefficients of variation for deposition and adaxial coverage (Table 3.3 and Table 3.6) are more similar to eachother than they are to the coefficients of variation of abaxial coverage (Table 3.4). This suggests that the higher levels of deposition are driven by greater deposits on the upper surface of the leaf – where coverage between the air blast and SSCDS are very similar.

Plots sprayed by the SSCDS show similar adaxial coverage but higher deposition than the air blast, suggesting that perhaps more chemical is being retained within the canopy since less is being lost to drift. This could have meaningful implications for drift reduction, since it suggests less chemical is being lost to the environment or blown beyond the rows. SSCDS systems may be able to spray at a lower rate than air blasts and achieve the same level of chemical deposition, which would reduce the amount of pesticides required for treatment, as well as the cost to growers. The coverage obtained by air blast sprayers and on the adaxial surface of SSCDS treated targets was also well in excess of the guidelines recommended by Holownicki (2002), which state that coverage over 30% is likely over spray. The air blast sprayer in this experiment was clearly over-applying, despite spraying at a relatively common rate per acre.

Despite differences in spray coverage and deposition, the SSCDS clearly showed that it obtained near equivalent pest management. There were two minor differences – the SSCDS had a higher incidence of fruit apple scab in 2016 (Figure 3.7), and slightly lower Obliquebanded Leafroller larval bioassay mortality in a 2014 (Figure 2.3). However, these differences were small, and all other season long pest management and bioassay data show no significant differences (Figure 2.5, Figure 3.8). Based on the most important aspect of spray application – control of the target pest, solid set systems provide a viable alternative to air blast sprayers. Air blast sprayers also have the advantage of nearly a century of modification, and future research into the SSCDS shows great potential for advancement.

Solid set canopy delivery systems offer an interesting new avenue of spray research, since very little work has been done in the field until quite recently. Most research has focused on whether systems can obtain comparable pest management to an airblast (Agnello and Landers, 2006; Niemann and Whiting, 2015; Verpont, 2015). Different models of emitters have been investigated by Sharda et al. (2015), along with different arrangements of microemitters. A great deal of additional work would be required to fully investigate the wide range of nozzles available commercially, as well as the operating pressure and time required for spray. With higher pressures, spray duration is shorter since more material is emitted in same amount of time. Changing application pressure changes the duration of the spray, and there may be advantages to longer spray periods that fill the air with droplets. Different nozzles also emit a wide spectrum of droplets, and finding the optimal spray pressure, nozzle, and duration will take a great deal of work. Additionally, while my studies anecdotally suggest that SSCDS can reduce drift and retain more chemical within the tree canopy, more research will be required to quantify the level of drift present in these systems compared to an air assisted sprayers. Preliminary results and observations show that wind speed and environmental conditions have a large impact on the SSCDS spray movement within the canopy, since droplets lack an air carrier and rely on ambient air movement to move laterally more than a meter. This will require further research and observations into whether SSCDS systems benefit from greater wind speeds, as well as the effect of wind direction relative to the tree row.

Regardless of modifications in timing and pressure, the SSCDS offers a tool for the rapid application of sprays. The current prototype can spray three rows in ten seconds, which opens up possibilities for temporal precision. With short spray times, growers may be able to complete spray rotations quickly, which could allow for reduced reapplication times at reduced rates (Grieshop, 2015). This may be extremely useful for conventional reduced risk compounds and biopesticides that have less residual time and more target specificity. The use of these compounds has been growing in the United States, as has organic apple production (Slattery et al., 2011), and an optimized SSCDS may assist in their delivery and efficacy.

Solid set canopy delivery systems may also be widely applicable to other crop profiles, the emitters utilized are adapted from greenhouse irrigation systems (Agnello and Landers, 2006), and installation of an SSCDS in this environment would be a logical progression of this research. Additionally, small fruit crops or other high density tree fruit systems with a planar architecture and trellis or support structure may be readily adaptable for SSCDS installation. We have presented preliminary findings of SSCDS coverage and deposition in grapes, blueberries and raspberries (Malsch, 2016). It is likely that each crop will have its own specific spray requirements and research would be required to ascertain the efficacy of an SSCDS applied spray as well as the emitters, configuration, and application pressures that optimize delivery.

APPENDIX

RECORD OF DEPOSITION OF VOUCHER SPECIMENS

The specimens listed below have been deposited in the named museum as samples of those species or other taxa, which were used in this research. Voucher recognition labels bearing the voucher number have been attached or included in fluid preserved specimens.

Voucher Number: 2017-13

Author and Title of thesis: Paul Owen-Smith, Pest Management Efficacy and Spray Characteristics of a Solid Set Canopy Delivery System in High Density Apples

Museum(s) where deposited:
Albert J. Cook Arthropod Research Collection, Michigan State University (MSU)

Specimens:

Family	Genus-Species	Life Stage	Quantity	Preservation
Tortricidae	*Choristoneura rosaceana*	larvae	5	alcohol
Tortricidae	*Choristoneura rosaceana*	larvae	5	alcohol

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