SOLID SET CANOPY DELIVERY SYSTEM: DRIFT REDUCTION, PEST MANAGEMENT, AND FRUIT QUALITY OUTCOMES

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ABSTRACT

Advances in apple cultivation, aiming to maximize the efficiency of harvest and yield per hectare, have led to the development of high-density apple orchards. High density orchards are characterized by densely planted narrow fruiting rows, with a "hedgerow" appearance. Whilst modern apple production has led to changes in orchard architecture, the technology used to apply agrochemicals has remained largely the same. The most commonly used technology to apply agrochemicals in apple orchards is the axial-fan Airblast sprayer. Unfortunately, these large, fan assisted sprayers were designed to treat larger more voluminous canopies leading to off target drift. An alternative spraying technology, the solid set canopy delivery System, or the SSCDS is a series of spray emitters placed in or above the canopy, making applications without the assistance of a large fan. Research into the plausibility of the SSCDS indicates that these systems are able to reduce off target drift while providing pest management equivalent to the commonly used axial-fan Airblast sprayer. A majority of the solid set systems assessed place emitters in the canopy which increases the chances for damage or emitter occlusion. The above canopy configuration reduces these chances, placing emitters overhead. This research was to quantify losses to ground as well as vertical and downwind off target drift produced by an above and in canopy SSCDS configuration compared to an axial-fan Airblast sprayer. Additionally, my research assessed the coverage, and deposition provided by two SSCDS configurations as well as season-long pest management, and fruit quality in orchards treated by an in canopy and above canopy SSCDS as well as an axial-fan Airblast sprayer. Off target drift measures suggest that vertical as well as downwind off target drift are significantly lower compared to drift produced by an axial-fan Airblast sprayer. Deposition measures indicated that both SSCDS configurations provided equivalent deposition throughout the canopy. Coverage however was greater at the top of the canopy and adaxial surfaces in trees treated by the above canopy SSCDS while coverage was more evenly distributed through the canopy in trees treated by the in canopy SSCDS. Pest management evaluations conducted in 2019 and 2020 detected little arthropod or disease damage in apples or foliage, damages similar in all treatments. Fruit quality assessments, including: size, weight and fruit count did detect differences between the SSCDS and axial-fan Airblast applications. The SSCDS configurations failed to adequately thin, apples leading to higher fruit counts in SSCDS treated trees. However estimated yield was not affected with similar metric tonnage per hectare determined for each treatment. These results suggest both the above canopy and in canopy SSCDS configurations produce significantly less off target drift compared to an axial-fan Airblast sprayer while providing adequate, equivalent pest management when compared to an axial-fan Airblast sprayer.

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"If I have seen further, it is by standing on the shoulders of giants" -Isaac Newton

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Chapter 1 - Literature Review

1.1. Introduction

Pest management in Michigan's apple (Rosaceae: *Malus domestica* L.) orchards presents a challenge as the climate is favorable to numerous diseases and arthropod pests. Effective pest management requires several plant protectant spray applications, up to twenty per year (Johnson, 2004; Holb et al. 2005; Jamar et al. 2010; Wise et al. 2015). The most commonly used technology to apply plant protectant agrochemicals such as insecticides and fungicides, is the axial-fan Airblast sprayer. Originally designed for treating large voluminous orchard canopies, the axial-fan Airblast sprayer remains largely unchanged since its inception (Fox, R., et al. 2008). Commercial apple orchards, however, have undergone significant change, from large voluminous canopies to short, narrow, high-density plantings. This has led to a mismatch between the axial-fan Airblast sprayer and the high-density apple orchards they serve, leading to spray materials passing through the canopy (Fox, R., et al. 2008; Kasnar et al. 2018). A potential solution to this mismatch is an array of micro-emitters, fixed to trellis rows, that are optimized to operate in narrow row crops. This approach will be described in this thesis.

Commercial apple production has been steadily moving towards high density orchards in order to maximize efficiency and ultimately, profitability. In order to maximize fruit production, canopies must receive the greatest amount of sunlight possible. Older growing methods that use larger canopied trees such as round crown shade the interior of the canopy (Wünsche & Lakso, 2000). Light levels within the first meter of the canopy can drop to 34% of full sunlight. Additionally, apples of high commercial quality do not appear on parts of trees exposed to less than 50% full daylight (Jackson, 1970). With the reduction of tree and canopy size, more light is allowed into the canopy, reducing the size of shaded areas and promoting higher yields (Robinson et al., 2013). The shorter trees and the less voluminous canopy also allow for easier pruning, as well as a more efficient and less laborious harvest. Apples can be harvested by hand from the ground and are much more concentrated in the growing space (Robinson, T., 2008). The high-density orchard is structurally very different from previous growing systems, requiring evaluation of how best to manage its pests and diseases.

1.2. Horticultural and Pest Management Spray Operations in Michigan orchards

Pest management in Michigan high density apple orchards requires controlling arthropod, fungal, and bacterial pests. Michigan's climate is favorable to several pest species requiring multiple pesticide applications per season (Wise et al., 2015; Jamar et al., 2010; Johnson, 2004). Several direct and indirect pests can damage apple orchards damaging both trees and fruit, leading to negative economic impacts. Direct pests are those who predominantly damage the fruit, while indirect pests are those that predominantly damage the rest of the plant (Demchak et al., 2023).

Direct arthropod pests in Michigan's apple orchards include Apple maggot, *Rhagoletis pomonella* (Walsh); Plum curculio, *Conotrachelus nenuphar,* (Herbst); Tarnished plant bug, *Lygus lineolaris*, (Palisot de Beauvois); Brown marmorated stink bug (BMSB), *Halyomorpha halys*, Stål; Oriental fruit moth, *Grapholita molesta*, (Busck); Codling moth *Cydia pomonella*, (L.); and the Oblique banded leafroller, *Choristoneura rosaceana,* (Harris). These arthropods directly damage fruit, causing fruit rot, fruit disfigurement, and fruit drop leading to both crop loss and unsalable fruit (Howitt 1993). Treatments commonly consist of properly timed foliar applications of organophosphates, carbamates, and pyrethroids, as well as pheromone disruption for Tortricid moths (Tortricidae), among others (Wise et al. 2022).

Indirect arthropod pests in Michigan's apple orchards include: Japanese beetle, *Popillia japonica,* Walsh; White apple leafhopper, *Typhlocyba pomaria,* McAtee; mites (Arachnida:Trombidiformes); and San Jose scale, *Quadraspidiotus perniciosus,* Comstock. These arthropods damage the tree by either feeding on fluids from the trunk and foliage, or consuming foliage. Feeding causes reduced vigor and other complications such as lower yield, the spread of disease, and ultimately the untimely death of the tree (Howitt 1993). Treatment commonly consists of properly timed foliar applications of organophosphates, carbamates, or METI (Mitochondrial complex 1 Electron Transport Inhibitors) acaricides for mites, among others (Wise et al. 2022).

Common diseases that affect Michigan's apple orchards include: apple Scab, *Venturia inaequalis* Cooke (Wint.)*;* Cedar apple rust, *Gymnosporangium juniperi-virginianae,* Schwein; powdery mildew, *Podosphaera leucotricha*, (E.S. Salmon); Sooty blotch/Flyspeck (fungal/bacterial complex). These diseases cause damage to foliage and fruit leading to defoliation, rot, reduced yield and disfigured fruit (Vaillancourt & Hartman, 2000; Strickland et al. 2020; Marine, et al. 2010; Williamson et al. 2000). Treatment consists of properly timed foliar applications of Sterol biosynthesis inhibitor (SBI), Succinate dehydrogenase inhibitor (SDHI), Anilino-Pyrimidine (AP), and Quinone outside Inhibitor (QoI) based fungicides, amongst others (Wise et al. 2022).

Necessary spray applications are not limited to pesticides; for instance, apple thinning compounds and foliar nutrition are also delivered by sprayer. Delivery of plant nutrients by way of foliar application is recommended as it poses the lowest risk of soil and groundwater contamination (Murtic et al., 2012). The addition of plant nutrition to an orchard treatment plan is often necessary to prevent diseases that occur when plant resources are exhausted. One such disease is bitter pit which occurs in Honeycrisp apples. Bitter pit occurs when trees are deficient in calcium, which can occur when trees are overcropped. This causes apple tissue to become soft and discolored, leading to fruit decay (de Freitas et al., 2010). To treat and prevent bitter pit, foliar applications of calcium chloride as well as apple thinning are recommended (Biggs et al. 2015). Fruit thinning reduces the number of apples per tree, preventing overcropping, which can lead to damaged limbs, low quality fruit, as well as bitter pit. Thinning can be achieved by applying plant growth regulators, as well as other compounds to the canopy, such as the combination of naphthalene acetic acid (NAA) and carbaryl (Dennis, 2000).

1.3. Agrochemical Applications in Orchards

The most frequently utilized sprayer in high density apple orchards in the United States is the axial-fan Airblast sprayer. This technology is fan-assisted, with adjustable banks of pressure-driven emitters whose products are carried throughout the canopy during applications. The predecessor to the modern axial-fan Airblast sprayer made its debut in 1949, patented by G.W. Daughtry. This early technology was an improvement over the application of dry pesticide via aircraft propeller and was shown to successfully control pests in citrus fruit. Post World War II, labor shortage, the development of effective pesticides, and the demand for high-quality fruit marked the rapid adoption and adaptation of axial-fan Airblast sprayers (Fox, et al. 2008). The popularity of the technology was based on its ability to make use of more concentrated forms of agrochemicals, which allowed for faster coverage of a larger area before the tank was emptied. The axial-fan Airblast also provided better coverage compared to previous application methods (Potts,1958). While the axial-fan Airblast sprayer is the most commonly used sprayer in high density apple orchards, it may not be the most appropriate.

The axial-fan Airblast sprayer is often affixed to or drawn by a large farm implement. When applying to orchard rows, the axial-fan Airblast sprayer is activated whilst being driven down multiple orchard rows. Repeated passage of large equipment can lead to damage to plants and infrastructure, as well as soil compaction (Becerra et al. 2010). Compaction can disrupt the rooting of plants, decrease oxygen diffusion in soil, and contribute to chemical runoff (Défossez et al. 2003). Additionally, the necessity of repeated passage also requires the burning of fossil fuels for each pass. Burning fossil fuels releases greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4). These Gases are suspected to have already increased surface temperatures 1.1 °C above pre-industrial levels. Rising temperatures have led to extreme weather, including storms and flooding which displaced a record 7 million people in the first half of 2019 (Jackson et al., 2020). While spraying agrochemicals produces lower amounts of carbon dioxide compared to other agricultural activities, improving the efficiency of all activities cannot be overemphasized (Lal, 2004).

While orchards have undergone drastic changes from large voluminous canopies to narrow hedgerow structures, the axial-fan Airblast sprayer remains largely the same (Fox, et al. 2008). This technology, which creates large plumes of spray, poorly targets the narrower orchard rows (Holownicki et al., 2000). Poor targeting may be attributed to the large powerful fan as well as the use of emitters originally designed for row crops. Emitters designed to treat row crops are made to spray downward onto a flat surface, rather than the complex, vertical structure of the high-density orchard canopy (Hoterman et al., 2017; Jones et al., 2000; Owen-Smith, 2017).

Common metrics used to assess spray technologies are coverage (percentage of surface covered) and deposition (quantity of material is deposited to a surface). These metrics are crucial for pest management, as pests can avoid contact with lethal doses of pesticide if an application results in inadequate coverage or deposition (Lewis et al., 2020). Axial-fan Airblast sprayers have been found to provide variable coverage and deposition: One study found an axial-fan sprayer had over-sprayed the lower portions of the canopy, while under-spraying the top (Brann, 1956). Greater deposition to the canopy can be achieved with higher wind speeds; this, however, leads to greater material ejected from the orchard (Jones et al. 2000). These materials ejected from the canopy contribute to off-target drift.

Drift is the movement of agrochemical dust or droplets through the air to any site other than the intended area (EPA.gov). Pesticide drift can lead to both economic and human health impacts: a 2011 study found that 37% to 68% of pesticide exposure illnesses reported by US agricultural workers were attributed to off-target drift (Lee et al., 2011). In Washington state alone, between 2005 and 2017, 56% of agricultural workers that reported illness due to pesticide exposure were exposed via off-target drift (Ford et al., 2017). Pesticides have been linked to increased chances of mutagenesis via bioassay, correlating agricultural worker exposure to pesticide and cancer risk (Blair & Zahm, 1995). Off-target drift produced by a sprayer can occur via spraying in improper weather conditions, spraying with an improper boom height, or, in the case of the axial-fan Airblast sprayer, inappropriate canopy size in relation to the sprayer (Arvidsson et al. 2011; Herrington et al. 1981). Air-assisted sprayers assessed in vineyards, which share the hedgerow structures of the high-density orchard, were shown to produce increased levels of drift with higher fan speeds (Pergher et al. 1995).

The axial-fan Airblast sprayer was designed for a different canopy: one taller, with greater volume compared to a high-density orchard (8m+ vs. < 4m tall). The combination of the large fan and narrow hedgerows increases the chances of off-target drift, with higher deposits downwind when compared to field crops. Drift associated with the axial-fan sprayer is caused by the horizontal vectoring and smaller droplets produced by the large fan, which are more prone to off-target drift (Hoterman et al. 2017; Kasnar et al. 2018; Ferguson et al. 2015). An experiment quantifying spray coverage provided by an axial-fan Airblast sprayer in hedgerow apple trees determined that 35% of a typical low-volume spray had been lost to the ground or as drift (Herrington et al. 1981). Additionally, even with the installation of drift-reduction technology, the axial-fan Airblast sprayer still shows the potential to produce off-target drift (Zhu et al. 2006).

1.4. Solid Set Canopy Delivery Systems

A possible solution for the issues of soil compaction, fossil fuel usage, and off target drift discussed above is a fixed agrochemical delivery system. These systems were developed to improve the application of agrochemicals in high-density trellised fruit crops. They are a fixed emplacement consisting of micro-emitters distributed along a trellised row. Emitters are fed by a large holding tank via irrigation lines hung on trellis wire and driven by hydraulic pumps; liquid is returned from the lines via an air compressor.

Early research into fixed agrochemical delivery systems began in the 1960s. These systems were composed of a network of impact sprinklers hung above the canopy of adult pear trees. The intent of the research was to compare the fixed agrochemical delivery system’s pest management capabilities to that of an axial-fan sprayer. This early system did not provide adequate pest management; however, the authors stated that with optimization the technology could be a competitive alternative (Lombard et al., 1966). Later, research into a similar system with micro emitters controlled by stop leak devices was proven to provide adequate pest management when compared to an axial-fan sprayer in an un-replicated experiment (Angello, A., & Landers, A. 2006). Building upon this design, a modern system was developed, known as the SSCDS (Solid Set Canopy Delivery System). SSCDS research continued in both high density apple orchards, vineyards, comparing the system’s efficacy to axial fan sprayers. Experimentation with the SSCDS included, but was not limited to, evaluations of coverage and deposition, off- target drift potential, fruit thinning, evaporative cooling, and pest management efficacy (Niemann et al. 2016; Sinha et al. 2019; Sinha et al. 2020; Owen-Smith et al. 2019; Sahni et al. 2022, Koonter 2023).

The potential for soil compaction, a threat posed by the axial-fan Airblast sprayer, could be drastically reduced. The SSCDS mentioned in this thesis is operated remotely, outside of the orchard rows, without the need to pass by every row using a tractor. Reduced fossil fuel requirements are also a strong probability as the SSCDS is stationary, and the system described in this thesis operates for less than 30 s.

Use of an SSCDS optimized for the narrower rows of a high-density orchard could provide treatments better suited to the new hedge-like rows (Owen-Smith et al., 2019). SSCDS configurations similar to the in canopy SSCDS described in this thesis, have been shown to provide adequate coverage and deposition, as well as adequate pest management (Angello, A., & Landers, A. 2006; Sinha et al. 2019; Owen-Smith et al. 2019; Sanhi et al. 2022). Unfortunately, with several pieces of equipment littered through the canopy, this configuration lends itself to being occluded by foliage or damaged during trellis maintenance or harvest, requiring further optimization. Chapter 3 describes pest management and fruit quality outcomes in a high-density apple orchard treated by the in canopy and above canopy SSCDS and axial-fan Airblast sprayer. This experiment compared the in canopy SSCDS with its commercially available emitters placed within the canopy, to an above canopy SSCDS with optimized static spreaders placed above the canopy along with the axial fan sprayer as a control.

The SSCDS is a possible drift reducing technology (DRT). Compared to the axial-fan Airblast sprayer, the SSCDS does not require a fan as part of its delivery scheme. The absence of a fan limits horizontal vectoring and small droplets produced by the turbulence of a fan. The SSCDS has been shown to produce significantly less off-target drift both above ground and downwind compared to an axial-fan Airblast sprayer in both high density apple orchards and vineyards (Sinha et al. 2019; Koonter 2023). Off-target drift has been measured for both an axial-fan sprayer and the SSCDS in both high density orchard and vineyard (Sinha et al. 2019; Grella et al. 2017; & Pergher et al. 1995; Zhu et al. 2006). However, at the time of writing no published data have analyzed drift produced by the SSCDS farther than 4.5 m downwind or greater than 0.9 m above ground and directly compared it to an axial-fan sprayer. Chapter 2 of this thesis reports on an experiment measuring off-target drift losses above, downwind, and in the orchard row at distances up to 64 m downwind of, and up to 12 m above the canopy.

1.5. Contents of this Thesis

The goal of this thesis research was to further explore the feasibility of an alternative agrochemical delivery technology, the Solid Set Canopy Delivery System (SSCDS). The objectives were to:

1) Compare the off-target drift potential of an in canopy SSCDS, an above canopy SSCDS, and an axial-fan Airblast sprayer (Chapter 2).

2) Identify if differences exist between coverage and deposition provided by the in canopy and above canopy SSCDS (Chapter 3).

3) Determine if the in canopy and above canopy SSCDS can provide season long pest management compared to an axial-fan Airblast sprayer (Chapter 3).

4) Determine if there are differences between the in canopy and above canopy SSCDS and axial-fan Airblast sprayer pertaining to fruit quality (size, weight, fruit per tree) in high density orchard after a season of agrochemical applications (Chapter 3).

Chapter 2 - Off-Target Drift Produced by the SSCDS vs. an Axial-Fan Airblast Sprayer

2.1. Introduction

Ideally, agrochemical delivery systems are designed for the crops they serve, optimized to deposit plant protection materials in the target area of the crop canopy and in the correct amount. When pesticide leaves the treatment area; as off target drift it can lead to a host of negative environmental, ecological, and economic impacts. Off target drift in particular carries with it the risk of negative environmental, commercial, as well as human health impacts. Drift is a significant factor when looking into human exposure and illness. For example, in Washington state between 2005 and 2017 56% of agricultural workers and 28% residential pesticide related illnesses were found to be the result of drift exposure (Ford, Dunn, Morrison, & Willis, 2017). Off target drift can be created from several situations not limited to: spraying in improper weather conditions, improper boom height, inappropriate spray implement use, or inappropriate canopy size in regards to a fan assisted sprayer (Arvidsson et al. 2011; Herrington et al. 1981).

Commercial apple production has been steadily moving towards high density narrow spaced orchards in order to maximize usable product per hectare and increase the efficiency of harvest. The shorter trees and smaller canopy allows for easier pruning as well as a more efficient and less laborious harvest as the apples are much more concentrated in the growing space. (Robinson, T., 2008) The most common spray technology used in apple orchards are fan assisted, axial-fan sprayers. Axial-fan sprayers often have adjustable banks of emitters whose products are carried throughout the canopy by the axial-fan sprayer’s powerful fan. The sprayer most used in high density apple orchards in the United States is the axial-fan Airblast sprayer (Fox, et al. 2008). These sprayers were originally designed for large voluminous canopies in orchards populated by much taller trees (8m+ vs. <4m tall). The powerful fan of the axial-fan sprayer in the narrow rows of the high-density orchard can not only break sprays into clouds of finer particles (which linger minutes to hours in the air), but particles not captured by smaller canopies can be carried long distances by wind. Applications in fruit crops by orchard sprayers show significantly higher downwind deposits when compared to field crops. This higher downwind deposition is mostly caused by horizontally vectored sprays produced by common orchard sprayers (Hoterman et al., 2017; Kasnar et al., 2018) Evaluations of drift, using air assisted implements in vineyards, which share the hedgerow like structure of the high-density orchard corroborate these findings of increased drift. Losses were shown to be upwards of 63% by Pergher et al. (1995) and up to 85% by Viret et al. (2003).

2.2. Solid Set Application Technology as a Drift Mitigation Technology

Drift reduction technology or DRT is technology engineered to reduce the off-target drift of applied agrochemicals. Droplet size is a contributor to off target drift, with smaller droplets being more prone to drift (Ferguson et al., 2015). Part of DRT involves the modification of equipment to increase droplet size without losing efficacy. Wind tunnel trials reveal that agrochemical sprays into wind currents resulted in smaller droplets at higher wind speeds (Hoffmann et al. 2011). The best practices handbook for axial-fan Airblast use, Airblast 101, recommends that to avoid drifting materials through and around the target canopy to slow the fan speed of the axial-fan Airblast sprayer. The small droplets influenced by the axial-fan Airblast sprayer's fan are more prone to drift as their small settling velocities can cause them to be deflected off from or carried past the target entirely (Deveau 47).

An alternative technology that does not make use of velocitized air is the Solid Set Canopy Delivery System (SSCDS). These systems are an in row, fixed emplacement shown to reduce off target drift when compared to axial fan spray applicators (Sinha, 2019). These systems also remove the need to drive heavy machinery into the treatment area to apply agrochemicals. This may mitigate soil compaction, equipment damage, and damage to the crop. Several of these in row, in canopy systems have been evaluated in high density orchards and vineyards. Agnello & Landers, (2006) developed an SSCDS with a mobile pumping system that showed equivalent pest management to an axial-fan sprayer when used in high density orchards. Similar equivalent pest management to an axial-fan sprayer in a high-density apple orchard was also determined by Owen-Smith (2019) and Sahni (2022). Carpenter, Reichard, & Wilson (1985) developed costs of infrastructure, data on nozzle selection, and analyzed economic feasibility of a proposed SSCDS, determining the technology could be feasibly implemented. Sinha (2019) determined the drift potential of an SSCDS and compared it to that of an axial-fan sprayer in a vineyard. Near field drift analysis (up to 4.5 m downwind) showed that depositions were higher downwind of the vineyard when using the axial fan sprayer. Sinha (2019) described the ability to automate an SSCDS removing the applicator from the field, reducing the probability of worker exposure. Thus, SSCD has the potential to reduce the probability of off-target exposure by removing personnel from the field and exposures caused by drifting agrochemicals.

Exploration of different emitters and emitter placement would allow SSCDS technology to be adapted to various crops and growing systems. Differing emitters and their placement can impact the coverage and deposition provided by the SSCDS as shown by Ranjan et al. (2021). An SSCDS with emitters distributed throughout the canopy as described by Owen-smith (2019) has the potential to be damaged by harvesting equipment or occluded by foliage. Variability in droplet sizes produced by emitters can increase the chances of drift with smaller droplet sizes more prone to becoming off target drift (Fox, R., et al., 2008; Ferguson et al. 2015). Evaluating an SSCDS with emitters overhead producing a larger droplet spectra may reduce both drift and potential equipment damage.

The literature available provides data on the behavior of materials distributed by axial-fan sprayers and SSCDS including off-target drift in vineyards and in high density apple orchards. (Sinha et al. 2019; Grella et al. 2017; & Pergher et al. 1995). However, data analyzing the behavior of drift farther than 4.5 m downwind and distances greater than 0.9 m above ground using an SSCDS have not been published. The evaluations of this study monitor in and near field drift as well as drift 12m above the ground and up to 64 meters downwind of the orchard along with losses to the ground in the drive row.

I hypothesized that two SSCDS configurations, one that is placed within the canopy and has a smaller droplet spectrum, and a second with micro sprayers solely above the canopy with a larger droplet spectrum, would produce less off-target drift than a Rears PB533N axial-fan Airblast sprayer. I also hypothesized that the above canopy SSCDS will produce less downwind drift than both the axial-fan sprayer and the in canopy SSCDS. In-row losses to ground were hypothesized to show greater deposition for both the above canopy and in canopy SSCDS configurations.

2.3. Materials and Methods

Two drift studies were conducted over the course of two years to determine the drift potential of an above canopy and in canopy SSCDS compared to a Rears PB533N axial-fan Airblast sprayer, referred to as Airblast in this document (Rears Manufacturing company, Coburg, OR, USA). In 2017 off-target drift produced by a Rears axial-fan Airblast Sprayer was compared to an SSCDS composed of micro sprayers distributed throughout the canopy (in canopy SSCDS). This experiment makes use of elements from similar experiments assessing off target drift and deposition (Khot et al., 2012; Salyani et al., 2000; Zhu et al., 2006).

In the 2018 experiment, the drift produced by an SSCDS with rotary emitters distributed above the canopy (above canopy SSCDS) was compared to the in canopy SSCDS and a Rears Airblast sprayer. The above canopy SSCDS was designed to explore the possibility of alternate emitter placements to reduce the probability of damage by removing emitters from within the canopy to above it, moving them out of the reach of equipment and contact with orchard personnel.

Experimental site. Drift evaluations took place at the Michigan State University Clarksville Research Center Clarksville, Michigan, United States (42.873933081589804, -85.25857635397287) in a high-density apple orchard. The treated area consisted of four 60 m rows of densely planted Honeycrisp apple trees (*Malus domestica*) approximately 2.5 m tall with 0.91 m spacing between trees and 3.66m row spacing. The tree rows were planted lengthwise, latitudinally (North/South) with the headland to the North side of the orchard. Upwind and downwind sides of the orchard facing East and West respectively. The area immediately downwind of the testing site, to the West, was mowed and field conditions were in accordance with ISO protocol (ISO, 2005).

Weather Data. Weather data was recorded per ISO 22522 (ISO, 2007) using an Airmax 150X (Airmar, Milford, New Hampshire, USA) weather station measuring temperature, relative humidity, windspeed, and wind direction. 2017 and 2018 Weather data is as follows: Temperature °C, Relative Humidity, Wind Speed minimum, Wind Speed maximum, Wind direction, Wind speed average. (Table 2)

General SSCDS design. The general SSCDS plumbing, and design used in these experiments were described in detail in Owen-Smith et al. (2019). The systems evaluated in my experiments consisted of 2.54cm diameter polyethylene irrigation lines (Toro, Bloomington, Minnesota, USA) hung at the top of each orchard row (2.5m), later called the application line, pressurized by a 212cc 598 lpm water pump (Loncin Motor Company, Chongqing, China) fed from a 1987 liter reservoir tank (Norwesco, St. Bonifacius, Minnesota, USA). Each application line supplied a series of emitters controlled by a 220.63kpa leak prevention device (Jain irrigation, Jalgaon, Maharashtra, India). The 2.54cm lines at the top of the orchard terminated into a parallel 1.91cm diameter polyethylene irrigation tube (Toro, Bloomington, Minnesota, USA) hung from the bottom trellis (0.9m) of the orchard row, the return line. This polyethylene tube terminated at the reservoir tank and served as a return line for unused material remaining in the system. The system's pneumatic pressure was driven by a Doosan 185 SCFM commercial air compressor (Doosan, Seoul, South Korea).

SSCDS application. The SSCDS operated in phases utilizing internal pressures to perform different actions. The first phase of this Solid Set Canopy Delivery System application was a low-pressure filling of the system (< 220.63 kpa) using two pumps, fed by a reservoir tank. The second phase was the application phase where the system was brought to high pressure (344.74 kpa), opening the leak prevention devices, and applying the spray treatment. Application rate was managed using time of application via stopwatch by which the number of emitters were active per hectare. Once desired application rate was reached the pumps were deactivated bringing the system below 220.63kpa closing the leak prevention devices and stopping the application. Phase three: return, was the return of remaining spray material from the irrigation lines back to the reservoir tank. During pressurization and application, a closed valve separates the application line from the return line. The large construction grade air compressor was plumbed into the 2.54cm application line, the valve between the application and return line was opened and air was applied at <220.63 kpa keeping the leak prevention devices closed and returning unused spray material back to the reservoir tank.

SSCDS and Airblast Systems. The in-canopy SSCDS emitters evaluated in the 2017 and 2018 drift experiments were composed of a Jain 7110 bridge with Jain 3044 impactors (Jain irrigation, Jalgaon, Maharashtra, India) installed within the canopy with a flow rate of 0.660 l/m and were placed every 0.609m with one emitter on the top trellis and a pair mid canopy, approximately 2.5 m and 0.9 m above the orchard floor, respectively. Each assembly of three emitters was controlled via a Jain leak prevention device. The above canopy SSCDS was composed of a Jain green fluid chamber fitted with a Jain gray rotary emitter attached to the same Jain leak prevention devices, one controlling each emitter. Each emitter had a flow rate of 1.59 lpm and were placed every 0.94 m on the top trellis wire, 2.5 m above the orchard floor. The Airblast used Teejet DC23 hollow cone, ceramic discs and whirl plates (Teejet Technologies, Glendale Heights, IL, USA). Calibration of the Airblast was performed with 10 nozzles at 69 kpa with a tractor speed of 6.1 km/h yielding an application rate of 458 l/ha. In 2017 and 2018, the Airblast sprayer was used to apply test solution to the experimental plots consisting of four rows, with both nozzle banks active when between rows, switching off the downwind facing bank of nozzles when applying to the orchard edge row.

The test solution consisted of water, 0.1% m/v Keystone pyranine 10G dye (Keystone Inc., Chicago, Illinois, USA), and 0.1% v/v commercially available non-ionic surfactant (Ragan & Massey Inc., Ponchatoula, Louisiana, USA). Treatment types (Airblast, in canopy SSCDS, and above canopy SSCDS) were applied randomly and independently from one another with samplers collected after each application. The 2017 experiment applied test solution for the Airblast and in canopy SSCDS three and four times respectively over the course of two days June 27, 2017 and July 14, 2017. The 2018 experiment applied test solution from the Airblast three times, in canopy SSCDS four times, and above canopy SSCDS four times, also over the course of two days August 9, 2018 and August 14, 2018. In order to develop a calibration curve a 20ml sample of the dye mixture was taken from the tank. For 2017 only one sample was taken for the entire experiment. In 2018 a sample was collected after every spray application.

Measuring in-row losses to ground. The 2017 and 2018 in row losses to ground measurements were collected using five parallel rows of 15.24 cm diameter polystyrene Petri dish lids (VWR International, Randor, Pennsylvania, USA), opening facing skyward and distanced 6m apart tracking South, away from the headland. Dishes were placed 0.5m apart in seven positions spanning East and West from the center of the tree row immediately east of the most westerly row (Fig 1 & 2). Positions were at 0m (Center)(center of tree row), ±.5m (Up 1, Down 1)(East and West drip edge of tree row canopy), ±1m (Up 2, Down 2), and ±1.5m(Up Center, Down Center)(the center of the drive rows East and West of the tree row) (Fig 4). In 2018 a 12.7 cm diameter piece of circular filter paper (Whatman, Maidstone, United Kingdom) was added to each Petri dish allowing for improved droplet collection during treatments. This paper impeded droplet reflection from the Petris dish's smooth surface. Collection of the ground loss Petri dishes was performed with gloved hands. Plates were rejoined with their associated half, sealed with Parafilm ®, and placed in coolers containing dry ice and insulated with canvas for transport. Post transport, samples were stored at -20°C until processed.

Vertical drift sampler collection. Vertical off target drift was measured by using polyester speargun string (Sgt. Knots, Statesville, North Carolina, USA) anchored to 8m and 12m tall telescopic poles (Jackite Inc., Virginia Beach, Virginia, USA) from 0m above the ground to either 8m or 12 m above the ground. The 2017 vertical flux deposition was measured via three 8m tall poles spaced 30 m apart (North/South) 0m downwind (West) of the last downwind orchard row (Figure 2.1). Vertical drift in 2018 was measured from three 8m poles in the same positions as 2017 with the addition of two 12m tall poles spaced 10m apart 8m downwind from the last downwind orchard row. (Figure 2.1 and 2.2) After each spray application, strings were carefully collected by two individuals with gloved hands. Strings were cut into 1 m segments and individually placed in 20 x 12 cm 6 mil plastic bags (US Plastics, Lima, Ohio, USA). Samples were placed in a cooler with dry ice, insulated by heavy canvas for transport until stored in freezers at -20°C.

Downwind drift sampler collection. The 2017 and 2018 downwind drift evaluations were assessed with 5 parallel rows placed north/south; samplers spaced 6m apart (North/South). Samplers consisted of 10.2 × 10.2 cm × 0.025cm Duralar mylar cards (Grafix, Cleveland, Ohio, USA) oriented parallel to the ground positioned incrementally downwind (West) of the orchard at distances of 0m, 1m, 2m, 4m, 8m, 16m, 32m and 64m as described in ISO standard 22866 and ASABE S561.1 (Figures 2.1 and 2.2). Mylar cards were harvested by gloved hands and placed into individual 20 × 12 cm 6 mil plastic bags. Bagged mylar cards were then placed in a cooler of dry ice insulated by heavy canvas for transport, then stored at -20°C until processed.

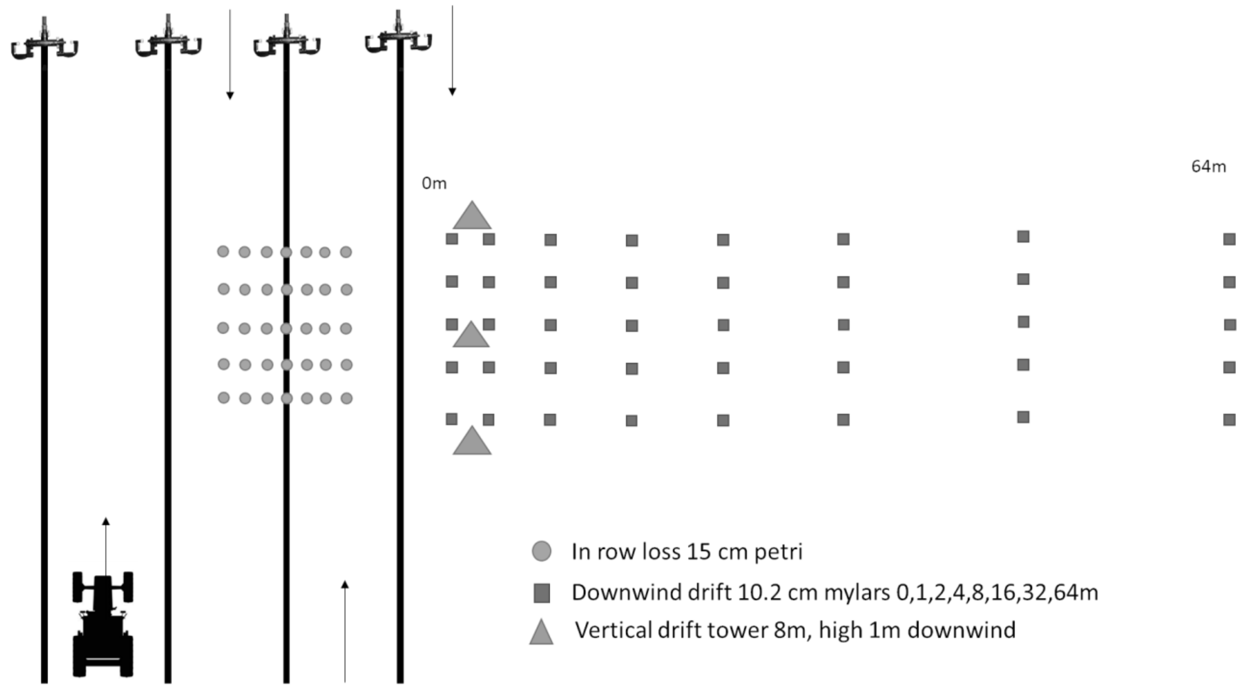

Figure 2.1 - Diagram of row, sampler placement, and sampler type for the 2017 Drift assessment. Arrows denote the direction of Airblast sprayer travel.

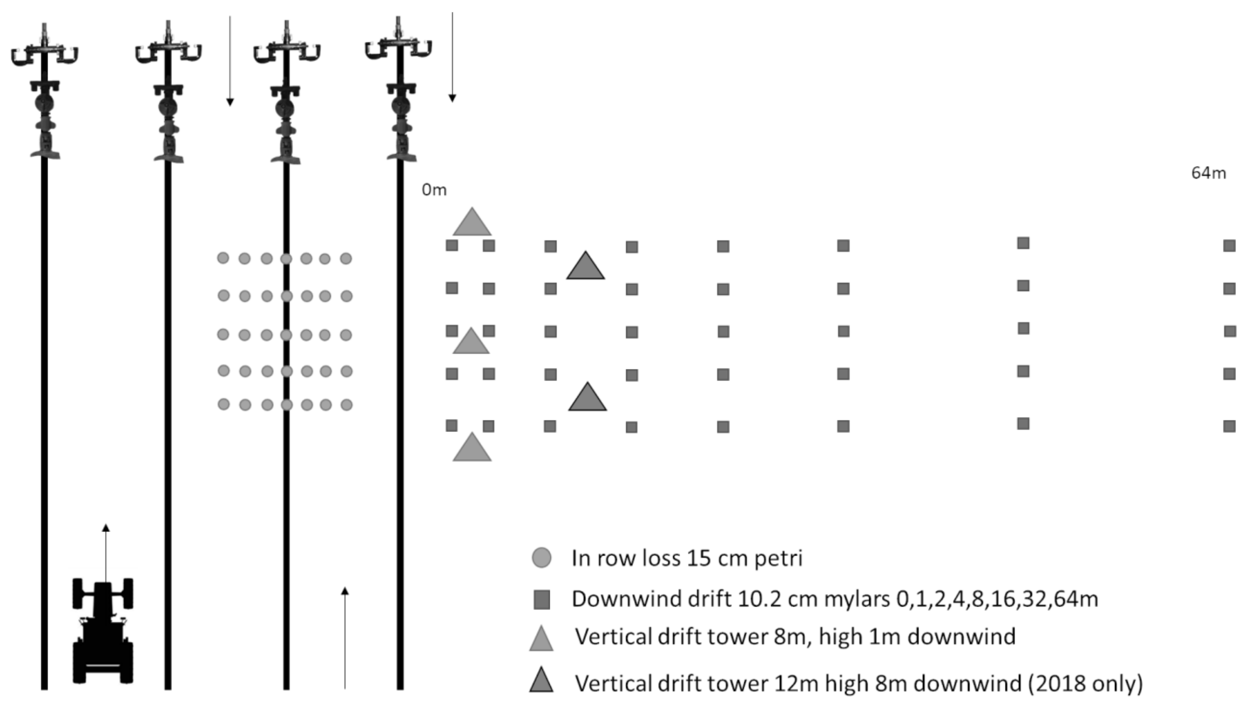

Figure 2.2 - Diagram of row, sampler placement, and sampler type for the 2018 Drift assessment. Arrows denote the direction of Airblast sprayer travel.

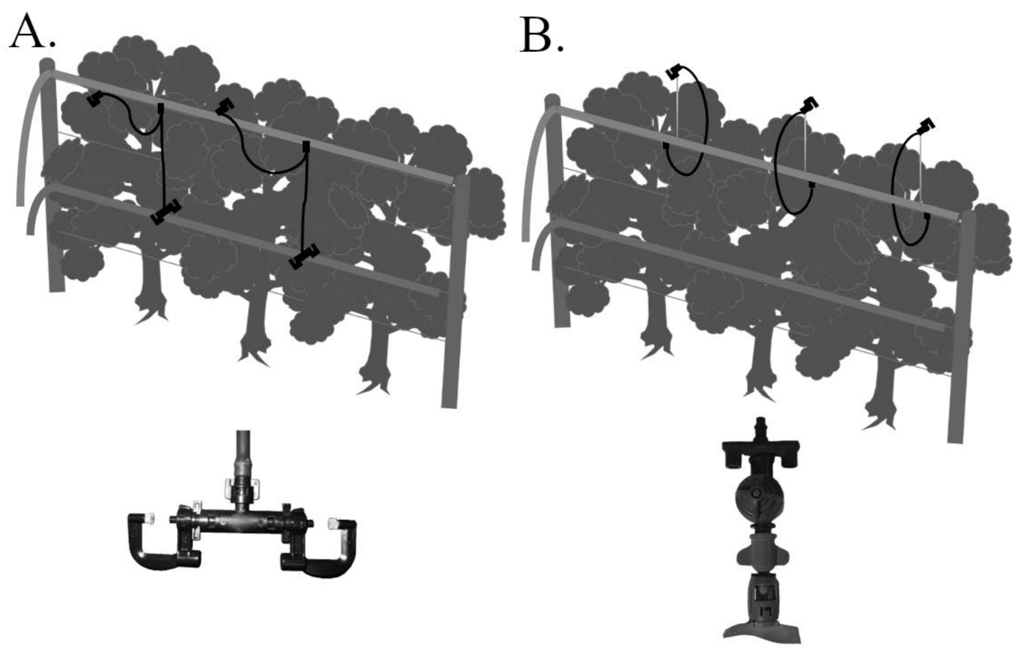

Figure 2.3 - Emitter placement in canopy and emitters. In canopy SSCDS, Jain 7110 nozzle body and impactor (A) Above canopy SSCDS, Jain green spinning emitter and stop leak device (B).

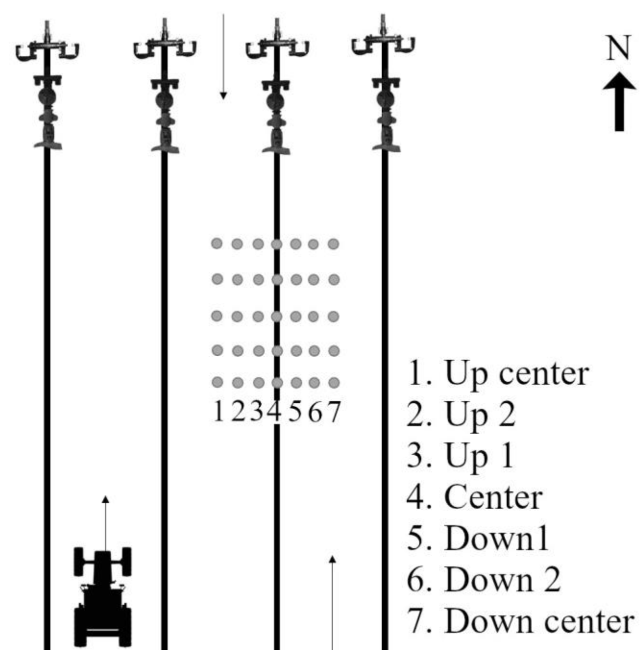

Figure 2.4 - Petri dish placement for collecting in row losses to ground.

Fluorometry Data Analysis. Fluorescence detection procedures are based on previous publications (Khot et al. 2012 & Salyani et al., 2000). A calibration curve was developed using tank samples collected during the experiments. The 2017 experiment made use of a single tank sample while the 2018 study used 11 (Four each for in canopy and above canopy SSCDS and three for the Airblast). Tank samples were diluted by a factor of 2 with 50% isopropyl alcohol water solution and then serially diluted by factors of 10, 100, 1000, 10,000 and 100,000 which corresponded to 0.5 g L^{-1}, 0.05 g L^{-1}, 0.005 g L^{-1}, 0.0005 g L^{-1}, 0.00005 g L^{-1} , respectively. Each one of these dilutions was added to three sequential chambers of a Trueline TR5002 24 well plate then analyzed with the Biotek Synergy HT spectrophotometer, excitation 400/30 and emission 540/25. The three sequential wells relative fluorescence units were averaged and the resulting number equaling an average of relative fluorescence units. Fluorescence values from the tank samples were used to create a nonlinear equations for each application that were used to estimate the mass of application in g cm^{-2}.

Table 2.1- Nonlinear equations generated from tank sample fluorescence, used to generate flux as a percent of the applied rate from deposition on samplers.

Year	Run	Treatment	Equation
2017			
	All	In Canopy SSCDS, Airblast	$(7 \times 10^{-16}X^3) + (1 \times 10^{-12}X^2) + (7 \times 10^{-9}X) + (7 \times 10^{-8})$
2018			
	1	Above Canopy SSCDS	$(2 \times 10^{-15}X^3) + (9 \times 10^{-13}X^2) + (1 \times 10^{-8}X) + (2 \times 10^{-8})$
	2	In Canopy SSCDS	$(4 \times 10^{-15}X^3) - (6\times10^{-13}X^2) + (3 \times 10^{-8}X) + (5 \times 10^{-8})$
	3	Airblast	$(5 \times 10^{-16}X^3) + (4 \times 10^{-12}X^2) + (1 \times 10^{-8}X) + (5 \times 10^{-8})$
	4	Airblast	$(5 \times 10^{-16}X^3) + (4 \times 10^{-12}X^2) + (1 \times 10^{-8}X) + (5 \times 10^{-8})$
	5	In Canopy SSCDS	$(2 \times 10^{-15}X^3) - (4 \times 10^{-13}X^2) + (2 \times 10^{-8}X) + (3 \times 10^{-8})$
	7	Airblast	$(4 \times 10^{-15}X^3) - (1 \times 10^{-11}X^2) + (2 \times 10^{-8}X) + (3 \times 10^{-8})$
	8	Above Canopy SSCDS	$(-5 \times 10^{-16}X^3) + (7 \times 10^{-12}X^2) + (2 \times 10^{-8})$

Dye release from samplers. The samplers placed for in-row ground loss, vertical drift, and downwind drift, the dye was released from the petri-dishes, strings, and mylar cards respectively, brought into solution using 10% v/v of 90% Isopropyl alcohol mixture in distilled water. All samples were first thawed, and following thaw a 20 ml aliquot of the alcohol mixture was added to Petri dishes, and bags containing mylar cards and strings. Bags were agitated ensuring all exposed surfaces were rinsed with the alcohol mixture. Petri dishes from the 2017 experiment were rotated ensuring all dye exposed surfaces were rinsed. The 2018 Petri dishes with the added filter paper were rotated exposing all surfaces to the solution and the filter paper was repeatedly folded and squeezed by a pair of sterilized forceps releasing trapped solution into the Petri dish.

Fluorescence Detection. Detecting fluorescence from drift samplers used 6ml of the dye/release agent solution. This solution was removed from the string and mylar bags along with the Petri dishes in 2 ml aliquots and pipetted into three sequential chambers of a Trueline TR5002 24 well plate (Corning, New York, USA). Using the spectrophotometer methods described above for the tank samples, three sequential wells were used to generate an average of relative fluorescence units (RFU) per sample. Using the calibration curve produced by the fluorescent dilutions from each independent tank sample each drift sample was converted from RFU's to grams per ml per meter squared using the two-dimensional area of the respective sampler. The grams per ml per meter squared detected on the sampler was then converted to a proportion of the applied rate by dividing the sampler deposition by the application rate in grams per meter squared at the known tank concentration.

Deposition Statistical Analysis. Deposition data was analyzed using RStudio (1.4.1717 ver. 3.4.0, R Foundation for Statistical Computing, Vienna, Austria) using a factorial analysis of variance (ANOVA) and post-hoc analysis using Tukey's HSD (honest significant difference) with a significance level of $\alpha=0.05$. Separate models were run for downwind drift, vertical drift, and in-row losses to ground for the response variable of proportion of applied rate. The proportion of the applied rate as flux was derived based on a protocol by Fritz et al. (2008), by dividing dye deposition to the sampler in grams per meter squared by the applied rate assuming 100% deposition to the sampler at the dye concentration of 0.1%. Arcsine transformations were carried out to ensure that data met assumptions of normality and heteroskedasticity. Treatments were in canopy SSCDS, above canopy SSCDS, and the Airblast sprayer. Distance from center of row (in row losses to ground), distance downwind from orchard (downwind drift), and distance above ground (vertical drift) were used as additional fixed factors. Akaike information criterion via the AICcmodavg R package was used to select the best fit between an interactive effect model or an additive effect model. Additive models were selected for 2017 vertical drift and in-row ground loss as well as 2018 8m and 12m vertical drift. Interactive models were selected for 2017 downwind drift as well as 2018 in-row ground loss and downwind drift.

2.4. Results and Discussion

Table 2.2 - Mean temperature, relative humidity, windspeed, and wind direction during applications in 2017 and 2018.

	Application	Treatment	°C	%RH	Windspeed ms^{-1}			Direction
2017					Min	Max	Mean	
	1	In Canopy	21.6	45.0	3.6	4.9	4.2	WNW
	2	In Canopy	21.3	45.0	2.5	4.4	3.4	W
	3	Airblast	21.7	42.0	2.0	5.8	3.9	WNW
	4	Airblast	21.8	42.0	2.4	5.5	4.0	WNW
	5	In Canopy	22.7	50.0	1.1	2.2	1.7	WNW
	6	In Canopy	23.4	57.0	3.1	4.8	3.9	W
	7	Airblast	22.8	55.0	1.3	3.8	2.6	WNW
	Mean	In Canopy	22.3	50.7	2.6	4.1	3.3	
		Airblast	22.1	46.3	1.9	5.1	3.5	
2018								
	1	Above Canopy	26.1	69.0	2.5	3.2	2.9	WSW
	2	In Canopy	25.6	70.0	1.1	2.8	1.9	WNW
	3	Airblast	27.2	65.0	1.1	1.3	1.2	WSW
	4	Airblast	27.8	63.0	1.3	1.3	1.3	W
	5	In Canopy	26.1	67.0	2.7	5.0	3.8	W-WSW
	7	Airblast	29.4	60.0	0.4	0.7	0.6	WSW
	8	Above Canopy	31.1	55.0	1.4	2.7	2.1	W-WNW
	9	In Canopy	30.0	48.0	1.8	4.0	2.9	WSW
	10	In Canopy	31.1	48.0	1.8	4.0	2.9	SW-WNW
	11	Above Canopy	30.0	50.0	2.7	5.1	3.9	W
	12	Above Canopy	28.3	50.0	3.0	4.9	4.0	W-WSW

Table 2.2 (cont'd)

Mean	In Canopy	28.2	61.7	1.9	3.9	2.9
	Above Canopy	28.9	56.0	2.4	4.0	3.2
	Airblast	28.2	62.7	0.9	1.1	1.0

2017 In row losses to ground. A significant difference was detected for the treatment main effect (Airblast and in canopy SSCDS) ($F_{1,234}$=22.38, p<.001), but not for the in row sampler position ($F_{6,234}$=0.42, p=0.87) (Table 3). Mean flux for the Airblast treatment ($\bar{x}$ =15.67% ±3.21%) did not statistically differ from the in canopy SSCDS ($\bar{x}$ = 10.73% ± 6.22%).

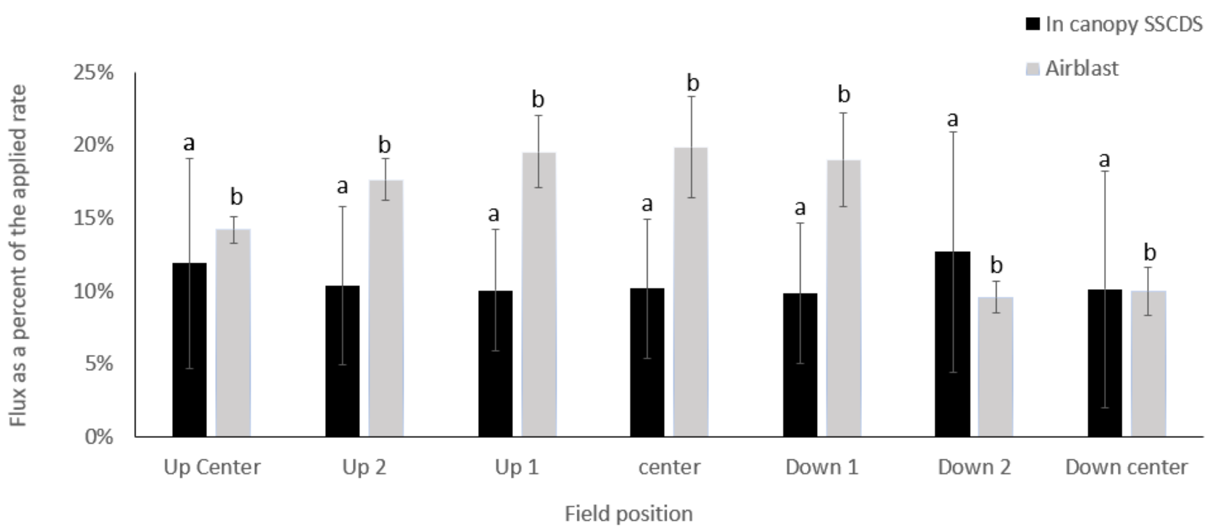

Figure 2.5 - 2017 Mean ± SEM flux as a percent of the applied rate as off target drift losses to ground. Differing letters signify statistically significant differences between treatments at α=0.05.

Table 2.3 - 2017 Mean ± SEM flux as a percent of the applied rate as off target drift losses to ground by treatment and field location. Differing letters signify statistically significant differences between treatments and field position at α=0.05.

Treatment	Field Location	Mean Flux (%)	±SEM	
In canopy	Center	10.17%	4.76%	a
In canopy	Down 1	9.82%	4.79%	a
In canopy	Down 2	12.68%	8.25%	a
In canopy	Down center	10.11%	8.12%	a
In canopy	Up 1	10.06%	4.18%	a
In canopy	Up 2	10.36%	5.43%	a
In canopy	Up Center	11.91%	7.20%	a
Airblast	Center	19.82%	3.47%	b
Airblast	Down 1	18.98%	3.21%	b
Airblast	Down 2	9.58%	1.05%	b
Airblast	Down center	9.98%	1.65%	b
Airblast	Up 1	19.53%	2.45%	b
Airblast	Up 2	17.63%	1.45%	b
Airblast	Up Center	14.19%	0.90%	b

2018 In row losses to ground. Significant differences were detected in treatment (Airblast, in canopy SSCDS, above canopy SSCDS), field position, and interaction factor ($F_{2,364}$=337.32,p<.001, $_{F6,364}$=7.97, p<.001, and $F_{12,364}$=7.60, p<.001 respectively). (Table 4)

Average flux for the Airblast treatment was lower than the above canopy SSCDS for all positions. Comparisons of the upwind and downwind samplers treated by the Airblast determined that samplers upwind received on average lower flux than those downwind. The greatest average flux for the Airblast samplers was detected in the Down 1 position ($\overline{x}$= 24.17% ± 5.34% flux). In contrast at this same position the above canopy SSCDS deposited ($\overline{x}$= 54.25% ± 12.10% flux).

Average flux was greatest for the in canopy SSCDS in the Up 1 position at ($\overline{x}$= 36.21% ± 8.27% flux) where it was the greatest of all three treatments at that position. Overall, the average flux deposited to the in canopy SSCDS samplers did not significantly differ across all positions. The in canopy SSCDS shows similar flux averages to the above canopy at the extents of the testing area in the Up Center and Down Center positions.

The above canopy SSCDS deposited the greatest amount of material of all the treatments, at the Center, Down 1, and Down 2 positions; these positions not only demonstrated the greatest average flux for the above canopy samplers but of all treatments and positions. ($\underline{x}$= 53.93% ± 8.51%, $\underline{x}$= 54.25% ± 12.10%, $\underline{x}$= 50.60% ± 14.45% respectively).

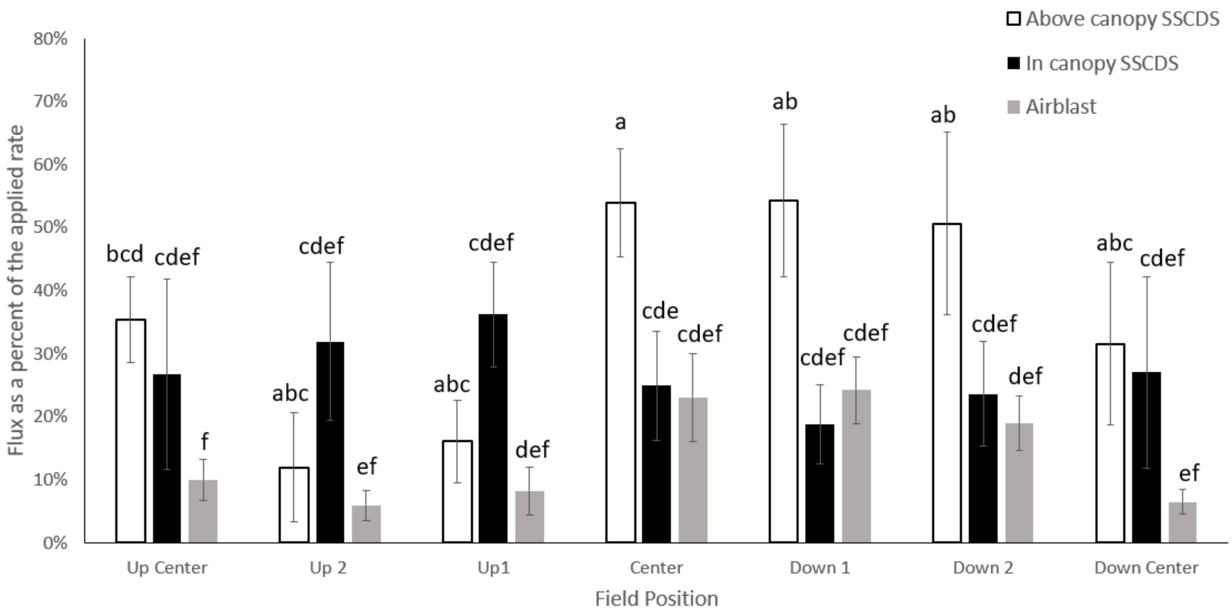

Figure 2.6 - 2018 Means ± SEM flux as a percent of the applied rate as off target drift losses to ground collected in various positions within the last two downwind orchard rows. Differing letters generated by Tukey's honest significant difference signify significant differences at α=0.05.

Table 2.4 - 2018 Mean ± SEM flux as a percent of the applied rate as off target drift losses to ground by treatment and field location. Differing letters signify statistically significant differences between treatments and field location at α=0.05.

Treatment	Field Location	Mean Flux (%)	±SEM	
Above canopy	Center	53.93%	8.51%	a
Above canopy	Down 1	54.25%	12.10%	ab
Above canopy	Down 2	50.60%	14.45%	ab
Above canopy	Down Center	31.54%	12.84%	abc
Above canopy	Up 1	16.09%	6.54%	abc
Above canopy	Up 2	11.97%	8.72%	abc
Above canopy	Up Center	35.41%	6.81%	bcd
In canopy	Center	24.89%	8.71%	cde
In canopy	Down 1	18.73%	6.30%	cdef
In canopy	Down 2	23.59%	8.27%	cdef
In canopy	Down Center	27.00%	15.12%	cdef
In canopy	Up 1	36.21%	8.27%	cdef

Table 2.4 (cont'd)

In canopy	Up 2	31.88%	12.51%	cdef
In canopy	Up Center	26.71%	15.10%	cdef
Airblast	Center	23.03%	6.97%	cdef
Airblast	Down 1	24.17%	5.34%	cdef
Airblast	Down 2	18.99%	4.32%	def
Airblast	Down Center	6.49%	1.88%	ef
Airblast	Up 1	8.14%	3.75%	def
Airblast	Up 2	5.90%	2.38%	ef
Airblast	Up Center	9.87%	3.27%	f

In row losses to ground comparisons. Overall mean flux values for 2017 were lower than those from 2018, this was likely due to the addition of the filter paper to the 2018 Petri dishes allowing for better droplet adhesion to the samplers. 2018 Airblast measures may also have been affected by windspeeds as they were lower on average compared to the SSCDS configurations. The 2017 Airblast and in canopy SSCDS mean flux did statistically differ between treatments however neither differed between sampler positions. The differences in 2018's experiment from 2017 allowed insight into the different deposition behaviors of the SSCDS configurations compared to the Airblast. In 2018, the Airblast was responsible for the lowest losses to ground, with average flux values downwind of the Center position with lower mean flux than both SSCDS systems. Mean windspeeds during axial-fan Airblast applications were lowest of the three treatments possibly effecting the percentage of flux detected. The Center position and the first two downwind positions show no statistically significant differences between both the in canopy SSCDS and the Airblast sprayer. By far the greatest flux via deposition to the ground was associated with the above canopy SSCDS. This is likely due to the greater flow rate and larger droplets produced by the emitters associated with the above canopy SSCDS. The greater mass of the droplets, thus their resistance to drift explain why the majority of the deposition remained in the row center and the first two downwind positions. The lower mean flux values of the in canopy SSCDS is hypothetically due to the lower flow rate and smaller droplet size, allowing for more material to distribute more evenly across the rows. While the mean depositions for the in canopy SSCDS are higher upwind they are not statistically significantly different than those immediately downwind. This pattern alluded to a somewhat more evenly distributed spray across the sampling area compared to the Above canopy SSCDS. Both SSCDS configurations had higher mean flux than the Airblast in upwind positions. The Airblast's fan, able to move large volumes of air containing velocitized droplets may be the reason for the lower deposits upwind, as the spray material influenced by the Airblast is more prone to downwind drift. This could also explain the lower overall deposition for the Airblast sprayer, as the material was dispersed and vectored away from the orchard rows.

2017 Vertical off target drift. Significant differences were detected for treatment (Airblast, in canopy SSCDS), and height above ground main effects. ($F_{1,135}$=148.73, p<.001, $F_{7,135}$=7.53, p<.001 respectively) (Table 2.5).

The Airblast deposited higher mean flux at every height sampled compared to the in canopy SSCDS. Mean Airblast flux peaked at 4m above ground at ($\bar{x}$= 25.11% ± 4.67%) with the Airblast minimum mean flux value at 8m above ground ($\bar{x}$= 3.46% ± 1.31%).

In canopy SSCDS mean flux declined with height, with similar mean values when comparing each height. (Table 5). In canopy SSCDS mean flux was greatest for the first two meters above ground, with nearly equivalent mean values ($\bar{x}$= 3.74 ± 1.44% and $\bar{x}$= 3.73 ± 0.95% respectively) that were approximately eight times lower than the mean flux determined for Airblast at these heights ($\bar{x}$= 23.15 ± 7.47% and $\bar{x}$= 21.05% ± 6.52% respectively).

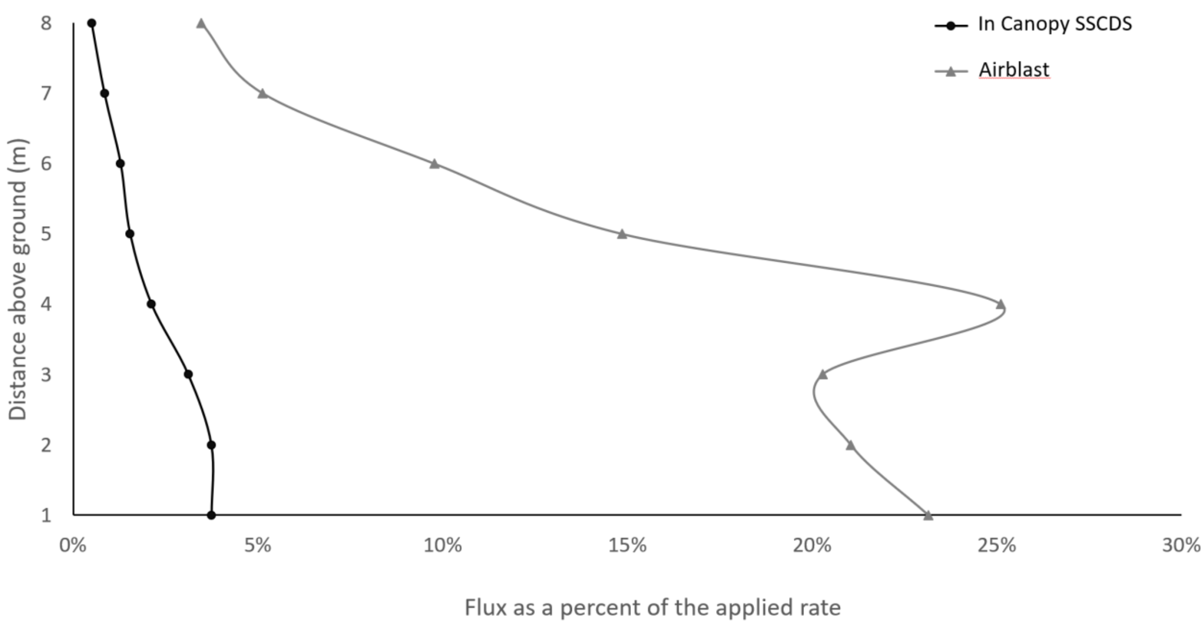

Figure 2.7 - 2017 Mean ± SEM flux as a percent of the applied rate as off target drift produced by the in canopy SSCDS and axial-fan Airblast sprayer from 1 m to 8 m above the orchard floor.

Table 2.5 - Mean ± SEM flux as a percent of the applied rate as off target drift from 1 m to 8 m above the orchard floor. Differing letters signify statistically significant differences between treatments and heights sampled at α=0.05.

Treatment	Height (m)	Mean %Flux	±SEM	
In Canopy	1	3.74%	1.44%	cde
In Canopy	2	3.73%	0.95%	cde
In Canopy	3	3.11%	0.61%	cde
In Canopy	4	2.12%	0.75%	de
In Canopy	5	1.54%	0.65%	e
In Canopy	6	1.28%	0.53%	e
In Canopy	7	0.85%	0.46%	e
In Canopy	8	0.50%	0.37%	e
Airblast	1	23.15%	7.47%	a
Airblast	2	21.05%	6.52%	ab
Airblast	3	20.28%	6.79%	ab
Airblast	4	25.11%	4.67%	a
Airblast	5	14.86%	7.72%	abc
Airblast	6	9.78%	3.11%	abcd
Airblast	7	5.13%	1.57%	bcde
Airblast	8	3.46%	1.31%	cde

2018 Vertical Off target drift: 8m collection poles. Significant differences were detected for treatment (Airblast, in canopy SSCDS, above canopy SSCDS) and height main effects (1m-8m) ($F_{2,238}$=176.4, p<.001, $F_{7,238}$=4.42, p<.001 respectively.) (Table 6).

Airblast mean flux peaked at 3m ($\underline{x}$= 65.67% ± 19.72%), this value is approximately thirty times and fourteen times respectively, larger than the mean values for the in canopy and above canopy SSCDS at this height ($\bar{x}$=5.12% ± 1.57% and $\bar{x}$=2.03% ± 1.32% respectively). Airblast showed greater mean flux when compared to the above canopy and in canopy SSCDS at all heights.

In canopy SSCDS mean flux values were inversely related to height with the greatest mean flux value at 1m above ground, ($\bar{x}$=10.88% ± 4.75%) and the lowest at 8m above ground ($\bar{x}$=0.34% ± 0.16%). In contrast, at 1m the Airblast's mean deposition value was nearly four times that of the in canopy SSCDS ($\bar{x}$=44.95% ± 13.49%). The in canopy SSCDS average flux reduced with height dropping below 1% average flux at 6m and above.

Similar to the in canopy SSCDS, the above canopy SSCDS mean flux was lower at each height sampled compared to the Airblast. The greatest mean flux for the above canopy SSCDS occurred at 1m above ground ($\bar{x}$=13.35% ± 7.34%) where it was approximately 3% larger than the in canopy SSCDS and approximately 32% lower than the mean flux of the Airblast at this height ($\bar{x}$ =10.88 ± 4.75% and $\bar{x}$=44.95% ± 13.49% respectively). The above canopy SSCDS minimum mean flux was detected at 8m above ground with the lowest mean flux of the three treatments ($\bar{x}$=0.06% ± 0.05%). In contrast, at the same height of 8m the average flux for the Airblast was ($\bar{x}$=29.57% ± 19.70%).

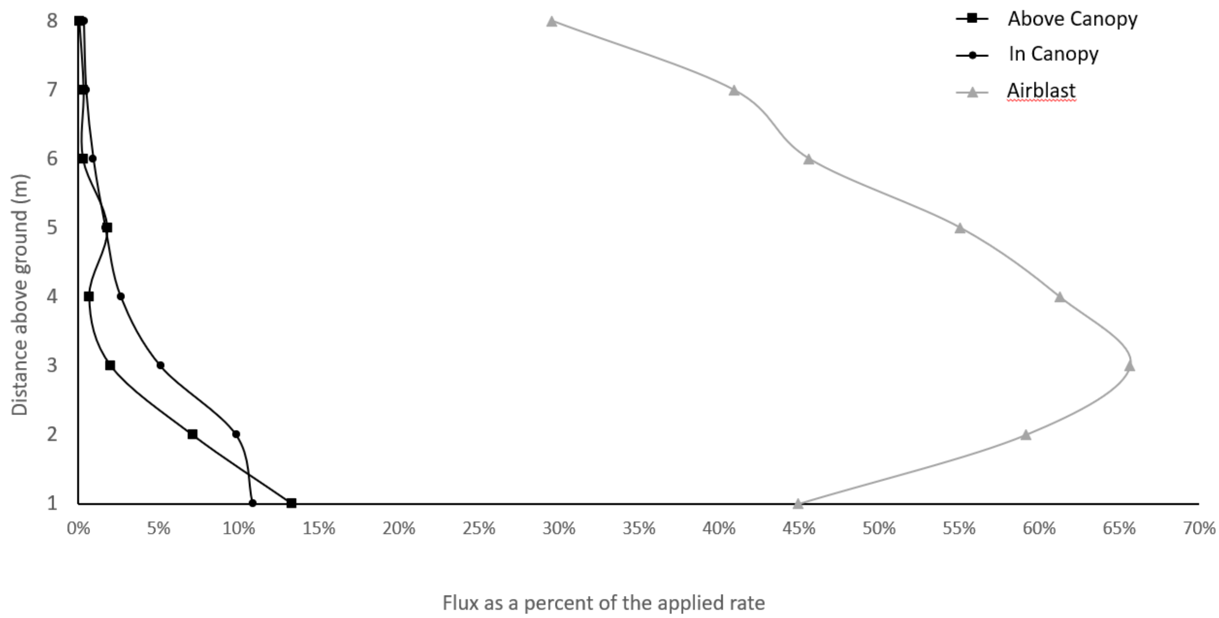

Figure 2.8 - 2018 Mean ± SEM flux as a percent of the applied rate as off target drift produced by the Above and in canopy SSCDS as well as Airblast sprayer from 1m to 8m above the orchard floor.

Table 2.6 - 2018 Mean ± SEM flux as a percent of the applied rate as vertical off target drift by height from ground from 1 m to 8 m above the orchard floor. Differing letters signify statistically significant differences between treatments at heights at α=0.05.

Treatment	Height (m)	Mean %Flux	±SEM	
Above canopy	1	13.35%	7.34%	cde
Above canopy	2	7.12%	4.84%	de
Above canopy	3	2.03%	1.32%	de
Above canopy	4	0.68%	0.36%	e
Above canopy	5	1.80%	2.67%	e
Above canopy	6	0.29%	0.38%	e
Above canopy	7	0.33%	0.44%	e
Above canopy	8	0.06%	0.05%	e

Table 2.6 (cont'd)

In canopy	1	10.88%	4.75%	cde
In canopy	2	9.85%	4.88%	cde
In canopy	3	5.12%	1.57%	de
In canopy	4	2.65%	0.92%	de
In canopy	5	1.69%	0.75%	e
In canopy	6	0.94%	0.60%	e
In canopy	7	0.49%	0.26%	e
In canopy	8	0.34%	0.16%	e
Airblast	1	44.95%	13.49%	ab
Airblast	2	59.15%	18.28%	ab
Airblast	3	65.67%	19.72%	a
Airblast	4	61.28%	21.39%	a
Airblast	5	55.08%	22.44%	ab
Airblast	6	45.64%	23.45%	ab
Airblast	7	40.92%	24.06%	abc
Airblast	8	29.57%	19.70%	bcd

2018 Vertical Off target drift: 12m collection poles. Statistically significant differences were detected in treatment (Airblast, in canopy SSCDS, above canopy SSCDS), and height from ground (1m-12m) ($F_{2,250}$=196.75, p<.001, $F_{11,250}$=6.70, p<.001 respectively).

Mean flux values for the Airblast were greater than both SSCDS configurations at all sampled heights. Mean flux detected for the Airblast peaked at 4m and was lowest at 12m ($\underline{x}$=30.74% ± 13.90% and $\underline{x}$=3.57% ± 3.02% respectively)(Table 7). Airblast flux values did not significantly differ from 7m to 12m above ground.

Mean flux values associated with the in canopy SSCDS peaked at two meters ($\underline{x}$=3.55% ± 1.07%), a significantly lower value than the Airblast at this height ($\underline{x}$=28.36% ± 8.32%). Mean flux values associated with the in canopy SSCDS decreased with ascending height dropping to zero at 10m above ground. The in canopy SSCDS was determined to have no significant differences between flux values at all sampled heights. (Table 7) The in canopy SSCDS and the above canopy SSCDS samples neared values close to zero at 9m and 8m above ground respectively.

Above canopy SSCDS average flux values were lower for all heights when compared to average flux values associated with the Airblast and in canopy SSCDS up to 9m where both SSCDS systems average flux neared zero. Above canopy SSCDS flux values were highest nearest the ground at 1m. Neither the in canopy or above canopy SSCDS statistically differed at any of the heights sampled. Contrasted with the Airblast, the Above canopy SSCDS mean flux peaked at 1m above ground at ($\underline{x}$=0.96% ± 0.55%) with the Airblast mean flux equal to ($\underline{x}$=23.92% ± 6.13%) at the same height (Table 7).

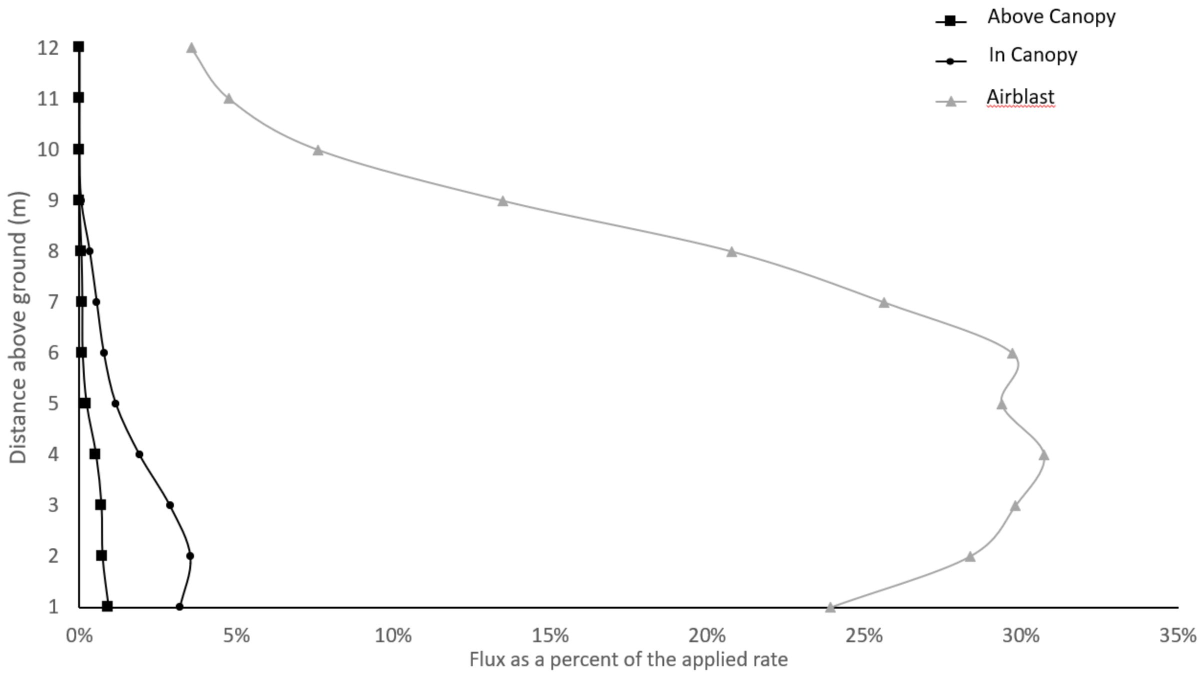

Figure 2.9 - 2018 Mean flux as a percent of the applied rate as off target drift losses from 1m to 12m above the orchard floor.

Table 2.7- 2018 Mean ± SEM flux as a percent of the applied rate as off target drift by height from ground using 12 m poles. Differing letters signify statistically significant differences between treatments at heights sampled at α=0.05.

Treatment	Height (m)	Mean % Flux	±SEM	
Above canopy	1	0.93%	0.56%	ef
Above canopy	2	0.74%	0.44%	ef
Above canopy	3	0.70%	0.40%	ef
Above canopy	4	0.54%	0.28%	f
Above canopy	5	0.23%	0.13%	f
Above canopy	6	0.10%	0.10%	f
Above canopy	7	0.10%	0.10%	f
Above canopy	8	0.07%	0.07%	f
Above canopy	9	0.00%	0.00%	f
Above canopy	10	0.00%	0.00%	f
Above canopy	11	0.00%	0.00%	f
Above canopy	12	0.00%	0.00%	f
In canopy	1	3.22%	0.92%	def
In canopy	2	3.55%	1.07%	def
In canopy	3	2.90%	0.89%	def

Table 2.7 (cont'd)

In canopy	4	1.93%	0.59%	ef
In canopy	5	1.17%	0.68%	ef
In canopy	6	0.79%	0.34%	ef
In canopy	7	0.56%	0.21%	ef
In canopy	8	0.34%	0.19%	f
In canopy	9	0.06%	0.08%	f
In canopy	10	0.00%	0.00%	f
In canopy	11	0.00%	0.00%	f
In canopy	12	0.00%	0.00%	f
Airblast	1	23.92%	6.13%	ab
Airblast	2	28.36%	8.32%	a
Airblast	3	29.83%	11.58%	a
Airblast	4	30.74%	13.90%	a
Airblast	5	29.39%	15.86%	a
Airblast	6	29.73%	19.31%	ab
Airblast	7	25.64%	17.09%	abc
Airblast	8	20.79%	13.97%	abcd
Airblast	9	13.48%	8.61%	abcde
Airblast	10	7.60%	4.98%	bcdef
Airblast	11	4.78%	3.89%	cdef
Airblast	12	3.57%	3.02%	def

Vertical Drift Conclusions. Mean flux was inversely related to sampler height on the 8m poles for both SSCDS configurations in both 2017 and 2018, as well as the 12m pole in 2018. The Airblast trends for both years and string sampler lengths reveal an increase in flux for the first few meters then decreasing with every meter after peak mean flux. SSCDS average flux values for both in canopy and above canopy did not statistically differ in both 2017 and 2018 for the 8m and 12m poles. Overall, the Airblast was responsible for the highest average flux at all heights for both years and both 8m and 12m sampling poles.

2017 Downwind off target drift. Significant differences were detected for treatment (Airblast and in canopy SSCDS), distance downwind, and interaction factor. ($F_{1,256}$=100, p<.001, $F_{7,256}$=47.49, p<.001, $F_{7,256}$=4.89, p<.001 respectively) (Table 8).

Mean flux was similar for both the Airblast and in canopy SSCDS at the 0m sampler. ($\overline{x}$= 14.49% ± 2.13% and $\overline{x}$ =16.09% ± 7.59% respectively) (Table 8). Samplers greater than 0m downwind recorded greater average flux deposited by the Airblast at every sampling distance. Both the Airblast and in canopy SSCDS deposited less than one percent flux at 64m downwind of the orchard.

The 2017 in canopy SSCDS mean flux peaked at 0m downwind ($\bar{x}$= 16.09% ± 7.59%) with reduced average flux for every sampler farther downwind than 0m. Average percent flux reduced with distance reaching below one at 16m downwind of the orchard ($\bar{x}$= 0.51% ± 0.12%). In contrast the average flux deposited by the Airblast at this distance was ($\bar{x}$= 5.29% ± 0.94%) and did not drop below 1% average flux until 64m downwind.

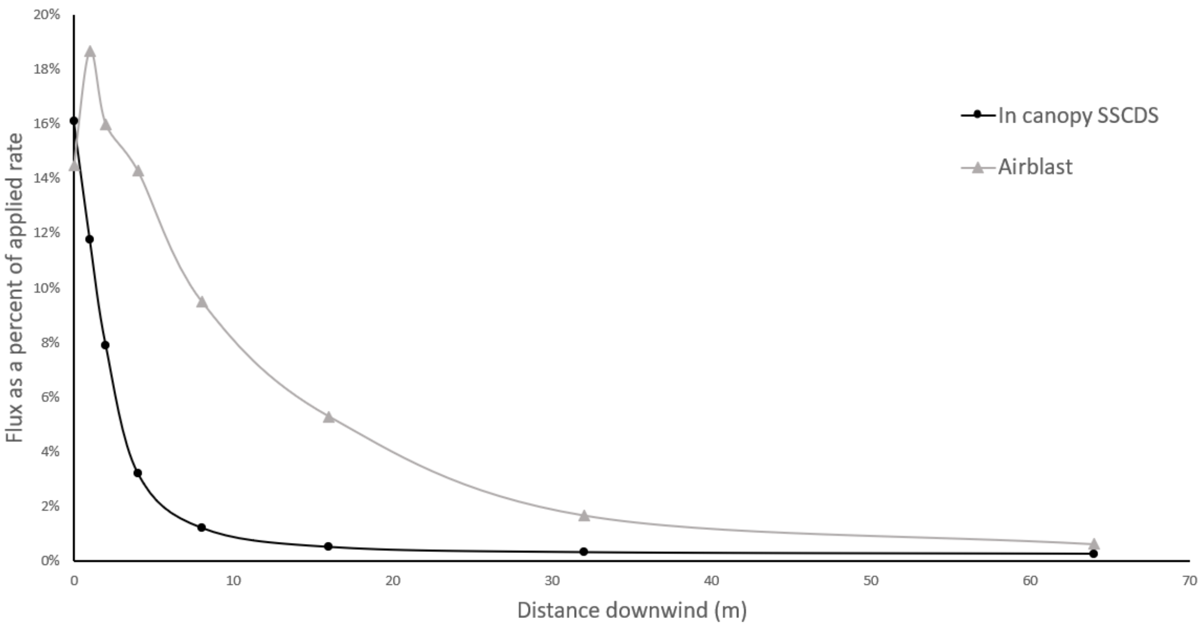

Figure 2.10 - 2017 Mean flux as a percent of the applied rate as off target drift downwind of the last orchard row.

Table 2.8 - 2017 Mean ± SEM flux as a percent of the applied rate as off target drift by distance downwind. Differing letters signify statistically significant differences between treatments at distances measured downwind at α=0.05.

Treatment	Distance Downwind (m)	% Flux	± SEM	
In canopy	0	16.09%	7.59%	cd
In canopy	1	11.75%	6.35%	de
In canopy	2	7.89%	3.93%	de
In canopy	4	3.22%	1.37%	e
In canopy	8	1.21%	0.42%	e
In canopy	16	0.51%	0.12%	e
In canopy	32	0.32%	0.04%	e
In canopy	64	0.26%	0.03%	e
Airblast	0	14.49%	2.93%	a
Airblast	1	18.66%	3.55%	ab
Airblast	2	15.99%	2.19%	ab
Airblast	4	14.29%	2.13%	ab

Table 2.8 (cont'd)

Airblast	8	9.51%	1.23%	ab
Airblast	16	5.29%	0.94%	abc
Airblast	32	1.67%	0.20%	bc
Airblast	64	0.62%	0.08%	cd

2018 Downwind off target drift. Significant differences were detected in treatment (Airblast, in canopy SSCDS, above canopy SSCDS), distance downwind, and interaction factor ($F_{2,411}$=204.24, p<.001, $F_{7,411}$=368.48, p<.001, $F_{14,411}$=30.36, p<.001 respectively.)(Table 9)

Average flux associated with the Airblast was greatest 2m downwind ($\overline{x}$= 24.43% ± 4.98%), similar to the mean flux detected for the above canopy SSCDS at the same distance ($\overline{x}$= 10.57% ± 4.65%). In contrast, mean deposition for the in canopy SSCDS at 2m downwind was lowest of the three treatments ($\overline{x}$= 3.84% ± 1.59 ng cm^{-2}). Airblast mean flux was greater than the in canopy SSCDS at all distances and was greater than than the above canopy SSCDS farther than 2m downwind.

In canopy SSCDS mean flux was lower than the Airblast for all distances sampled, with the greatest disparity at 4m downwind with the in canopy SSCDS mean flux approximately ten times lower than the Airblast ($\overline{x}$= 1.84% ± 0.69%, $\overline{x}$= 18.88% ± 4.09% respectively). At 4m downwind average flux for both the in canopy and above canopy SSCDS were near equivalent ($\overline{x}$= 1.84% ± 0.69%, $\overline{x}$= 1.52% ± 0.84% respectively.), remaining so with increasing distance, both dropping under 1% at 8m downwind.

The above canopy SSCDS's highest mean flux was at 0m ($\overline{x}$= 24.47% ± 5.49%). This value is approximately two times greater than the in canopy SSCDS ($\overline{x}$= 10.20% ± 3.04%) and is similar to the Airblast ($\overline{x}$= 27.74% ± 4.80%) at this distance. As distance downwind increases, average flux values for the above canopy SSCDS reduce, equalizing with the in canopy SSCDS at 4m as described above. At 4m downwind the above canopy SSCDS mean flux ($\overline{x}$= 1.52% ± 0.84%) is approximately twenty times less than its mean flux at 0m downwind ($\overline{x}$= 24.47% ± 5.49%).

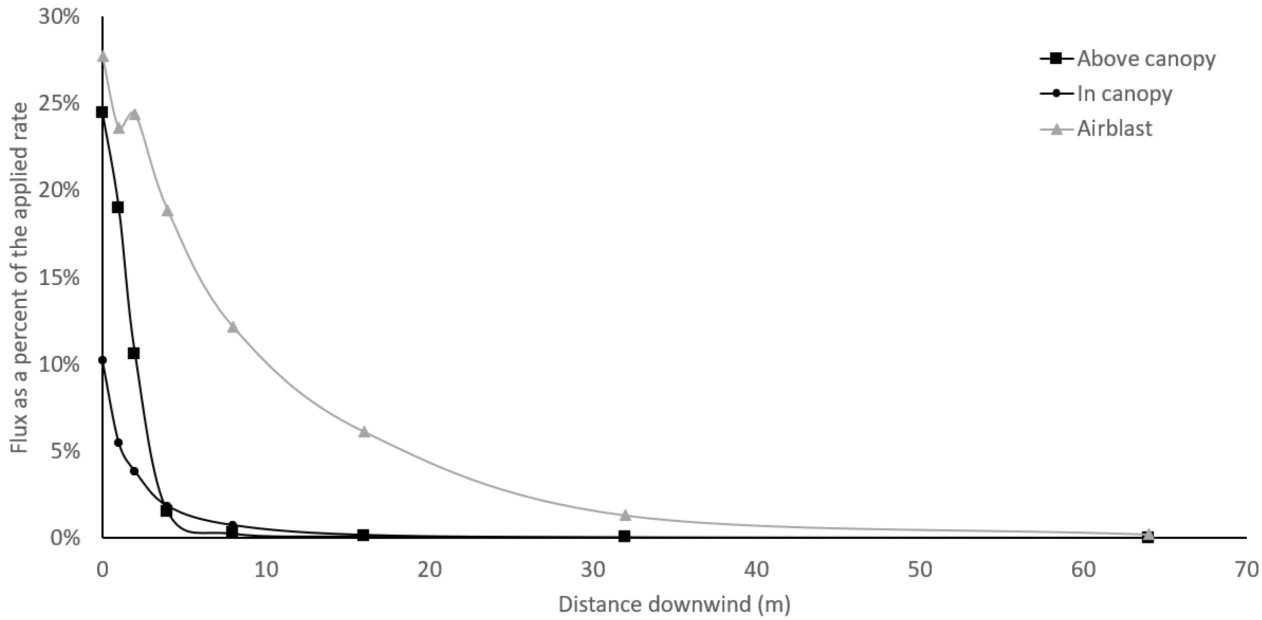

Figure 2.11 - 2018 Mean flux as a percent of the applied rate as off target drift downwind of the last orchard row.

Table 2.9 - 2018 Mean ± SEM flux as a percent of the applied rate as off target drift by distance downwind. Differing letters signify statistically significant differences between treatments at distances measured downwind at α=0.05.

Treatment	Distance (m)	% Flux	±SEM	CLD
Above canopy	0	24.47%	5.49%	a
Above canopy	1	18.99%	5.74%	ab
Above canopy	2	10.57%	4.65%	ab
Above canopy	4	1.52%	0.84%	ab
Above canopy	8	0.28%	0.19%	abc
Above canopy	16	0.11%	0.07%	bc
Above canopy	32	0.03%	0.01%	cd
Above canopy	64	0.01%	0.01%	de
In canopy	0	10.20%	3.04%	hij
In canopy	1	5.49%	1.95%	hij
In canopy	2	3.84%	1.59%	hij
In canopy	4	1.84%	0.69%	ij
In canopy	8	0.75%	0.28%	ij
In canopy	16	0.18%	0.07%	ij
In canopy	32	0.05%	0.02%	j
In canopy	64	0.02%	0.01%	j
Airblast	0	27.74%	4.80%	de
Airblast	1	23.63%	3.85%	def

Table 2.9 (cont'd)

Airblast	2	24.43%	4.98%	ef
Airblast	4	18.88%	4.09%	fg
Airblast	8	12.16%	3.02%	gh
Airblast	16	6.13%	1.74%	ghi
Airblast	32	1.31%	0.28%	ghij
Airblast	64	0.21%	0.06%	hij

Downwind off target drift observations. The 2017 and 2018 downwind off target drift measurements revealed an overall pattern of reduced mean flux the greater the distance downwind of the orchard for both SSCDS configurations and the Airblast. The only departure from this pattern is for the 2017 Airblast, in which flux increased from 0 m to 1 m downwind but declined with distance greater than 1 m downwind. For both 2017 and 2018 a majority of average flux occurred nearest the orchard with the highest flux within the first 4m downwind. The Airblast's mean flux, while declining with distance downwind from the orchard, remained greater than both the in canopy and above canopy SSCDS overall. For 2017, distances greater than 1m and for 2018 distances greater than 2 m show the Airblast with greater mean flux. Disparities occurring 2 m - 16 m downwind, range anywhere from near equal to several times greater mean flux produced by the Airblast, compared to the SSCDS configurations for both years.

Greater flux was detected downwind and above the orchard when the Airblast made applications and was most likely due to the Airblast's powerful fan used for delivering agrochemicals. The fan vectored materials away from the sprayer moving large volumes of air during applications which, in mis-matched canopy, are more prone to downwind drift (Herrington, et al., 1981; Triloff, 2015). The in canopy SSCDS's delivery in contrast did not make use of a fan and materials were vectored mostly downward. Hypothetically, downward vectoring and lack of velocitized air in a mismatched canopy is why a majority of the average flux deposited by the in canopy SSCDS is nearest the orchard and was lower than the Airblast overall. This may also explain the higher flux depositions detected on the ground when using the SSCDS configurations. Similar findings of reduced downwind deposition were published by Washington State University comparing the SSCDS to an Airblast sprayer in vineyard (Sinha et. al., 2019).

The greatest average flux occurred in 2018 using the above canopy SSCDS which had significantly greater deposition than both the Airblast and in canopy SSCDS for the 0 m and 1 m downwind samplers. The above canopy system includes spinning emitters with greater output volume per emitter than the in canopy SSCDS and whose droplet spectra is coarser. The higher volume emission and greater mass, drift resistant droplets are a likely explanation for the greater deposition nearest the orchard and lower mean deposits downwind when comparing the above canopy SSCDS with the Airblast.

These findings as well as findings by (Balsari et al., 2014) as well as assessments into near field drift by (Sinha et. al., 2019) suggest that the large volume of air disturbed by axial-fan Airblast sprayers velocitizes spray material, and in smaller canopies increases the potential for material to travel downwind from the orchard, creating downwind off target drift. Overall, determining the amount of material leaving the orchard as non-target downwind drift, both SSCDS configurations displayed lower downwind mean depositions.

Off target Drift. These experiments indicate the delivery of agrochemicals via the axial-fan Airblast sprayer is more prone to vertical and downwind off-target drift compared to the two SSCDS systems evaluated. Axial-fan Airblast sprayers were designed for spray applications in large and voluminous canopies, not the short, narrow canopies typical of modern high-density apple orchards (Hoterman et al., 2017). Fan-assisted technology, like the axial-fan Airblast make use of the disturbance of large volumes of air to deliver its agrochemical payload. The SSCDS, lacking the high velocity vectoring and wind shear, appear to contain spray applications closer to the targeted orchard rows. Further evidence for the reduction of drift away from the orchard may be explained by the higher mean deposition values present using the SSCDS configurations in the losses to ground measurements. Findings by (Owen-Smith 2019) suggest that higher overall canopy depositions may exist for the SSCDS when compared to an axial-fan Airblast sprayer. Similar data published by Washington State University suggests that compared to an axial-fan Airblast sprayer, the SSCDS lacking the fan assisted delivery, is less prone to downwind drift (Sinha et. al. 2019).

2.5. Conclusions

This study determined spray deposition in the form of off target drift produced by two configurations of the Solid Set Canopy Delivery System (in canopy and above canopy) vs. a axial-fan Airblast sprayer. Losses to ground were higher when applying with the SSCDS compared to the axial-fan Airblast sprayer. Vertical drift flux measurements suggested that overall drift above the orchard floor when using the Airblast sprayer is greater than that of both SSCDS configurations. The SSCDS showed significant reduction of downwind and vertical drift produced by the Solid Set Canopy Delivery Systems compared to the Airblast. With lower depositions downwind and above the canopy and higher depositions to the ground using the SSCDS, suggests that more material is leaving the orchard as off-target downwind drift when using an Airblast sprayer compared to either SSCDS configuration. The results of this study are in support of the further development of the SSCDS as an effective, drift reducing agrochemical delivery system in high density apples.

Chapter 3 - SSCDS Pest Management and Fruit Quality Outcomes

3.1. Introduction

The Solid Set Canopy Delivery System (SSCDS) was developed as an alternative application method to improve the delivery of agrochemicals in high-density trellised fruit crops. The SSCDS is a fixed emplacement consisting of micro-emitters distributed along a trellised row. Emitters are fed by irrigation lines hung on trellis wire and driven by hydraulic pumps. This technology operates without heavy tractor-driven equipment or personnel needing to access the application area. Repeated passage of farm equipment leads to the compaction of soils, especially in places that receive elevated levels of rainfall. Compaction can hinder the rooting of plants, decrease oxygen diffusion, and lead to chemical runoff (Défossez et al., 2003). The SSCDS's network of emitters can be operated from a single point, delivering agrochemicals without requiring equipment to make a series of passes within an orchard, reducing soil compaction, time, and the fuel used to make multiple trips.

This technology also reduces the risk of worker exposure to agrochemicals by removing personnel from the treated area as well as reducing the amount of material lost as off target drift. Pesticide drift is defined as the movement of dust or droplets that move through the air to any site other than the area intended (EPA.gov). SSCDS systems have been shown to reduce off target drift when compared to axial fan sprayers in both grapevines and high-density apple orchards (Sinha et al., 2019; Koonter, 2023).

Similar solid set systems have previously been explored. Beginning in the 1960's at the Southern Oregon Experiment Station an overhead system was developed that placed sprinkler heads above the canopy of pear trees. An experiment was conducted comparing the system's ability to provide pest management to an axial-fan sprayer. Due to technical limitations of the time, the system was not able to provide adequate pest management. The author states that improvements to this type of application method could make it a competitive alternative (Lombard et al., 1966). Later experiments would look to improve upon the design and cost of the system, exploring the integration of check valves, positive shut off valves, anti-siphon valves, micro emitters and chemical resistant parts preventing contamination caused by leaking or backflow of agrochemical into water sources (Threadgill, 1985; Carpenter et al.,1985, Wilson, 1983; Sawyer & Oswalt, 1983).

In 2005 a network of micro-emitters controlled by stop leak devices, distributed through the canopy of a high-density orchard in New York was able to provide adequate pest management comparable to a commonly used axial fan sprayer (Angello, A., & Landers, A. 2006). More recent research has built upon this with installations of solid set canopy delivery systems installed in both high-density apple orchards and grape vineyards in Michigan and Wanshington State. Evaluations of these systems describe coverage, deposition, decreased off target drift potential, and adequate pest management provided by the SSCDS (Sinha et al., 2019; Sinha et al. 2020; Owen-Smith et al., 2019; Sahni et al., 2022). Evaluations of alternative emitters, and emitter placement have also been explored. Various emitter types have been assessed both in and above the canopy attempting to optimize treatment provided by the SSCDS (Ranjan et al., 2021). High density apple orchards for instance have tall narrow fruiting walls, so adjusting emitter spray patterns and placement to treat within a limited area is required to maximize coverage and deposition and reduce product losses.

In apple production, the move towards high density fruiting walls is based on maximizing yield by planting as many trees as possible in a space without incurring negative effects caused by overcrowding. This method also allows for easier pruning and less laborious harvest (Robinson et al., 2013). These narrower, thinner canopies are a mismatch for the technology most commonly used to apply agrochemicals to them, the fan assisted axial sprayer. These sprayers were developed to treat orchard systems with taller more voluminous canopies. This mismatch leads to the off-target drift of applied agrochemicals (Fox R., et al. 2008; Holterman et al., 2017; Kasner et al., 2018). The SSCDS is a possible solution for a more optimized delivery of agrochemicals is the Solid Set Canopy Delivery System.

Solid Set Canopy Delivery Systems produce dramatically less drift than axial fan sprayers because they do not require active air movement as part of the application process. It has been shown that when compared to an axial fan sprayer the SSCDS can reduce drift both above and downwind of the application area. (Sinha et al. 2019; Koonter 2023). Experiments conducted in a high-density apple orchard over a two-year period, determined that the in canopy SSCDS produced significantly less off target downwind drift compared to an axial fan sprayer. This study monitored drift deposits up to 64m downwind of the orchard and found that both SSCDS configurations' mean deposition reached zero at approximately 16m downwind and the axial fan sprayer mean deposition was still detectable at up to 64m downwind of the orchard (Koonter 2023). While the technology does have the ability to reduce off target drift when compared to an axial fan sprayer, the SSCDS must also provide pest management with better or equal efficacy if it is to be adopted.

Research conducted by Owen-Smith (2019) demonstrated that an axial-fan sprayer provides greater coverage to the underside of leaves than the in-canopy SSCDS, but coverage is near equivalent for the topside of the leaves comparing both the in-canopy SSCDS and the Axial fan sprayer. Overall greater deposition to the canopy exists for the in-canopy SSCDS when comparing it to an axial-fan sprayer. This relationship was also described by Washington State University evaluating an SSCDS in a vineyard (Sinha et al., 2020). While disparities exist for coverage and deposition between the in-canopy SSCDS and the axial-fan sprayer, this does not seem to influence pest efficacy as both were shown to provide equivalent pest management (Owen-Smith et al., 2019; Sahni et al., 2022).

Pest management in Michigan apple orchards requires management of a variety of arthropod, fungal and bacterial pests. Temperate climates like Michigan's, are favorable to several pest species requiring fifteen to twenty plant protectant sprays per year, oftentimes weekly from April to June (Johnson, 2004; Holb et al., 2005; Jamar et al., 2010; Wise et al., 2015).

One of the most common diseases in Michigan apples is apple scab, which is caused by *Venturia inaequalis,* a fungal pathogen. This pathogen overwinters in fallen leaf tissues in its sexually reproductive form and after reproduction disperses to young apple tissues under wet conditions (Vaillancourt & Hartman, 2000). Seventy-five percent of agrochemical treatments from April to June are applied to control apple scab (Johnson, 2004). Control of apple scab requires frequent application of fungicides, oftentimes after rainfall. (Koetter 2019). Other diseases affecting Michigan apples include: Cedar apple rust (*Juniperus virginiana)*, powdery mildew (*Podosphaera leucotricha*), and sooty blotch/flyspec (microbial complex) and disorders like bitter pit.

Cedar apple rust is a fungus that infects apple foliage and fruit but requires an alternate host to reproduce, like trees of the *Juniperus* genus. When cedar apple rust spores spread from alternate hosts, they begin their infection of young apple tissues. One to two weeks later, red-orange lesions begin to form on the surfaces of the leaves and fruit. Recommended control is the removal of host plants from near the orchard, planting of resistant cultivars, and treatment with fungicide (Strickland et al., 2020).

Powdery mildew is a fungal pathogen that infects both apple leaves and fruit. Colonized young tissues of terminal buds have a silver-gray appearance and the infection leads to defoliation, stunted growth, and die back. Infections of the blossom or developing fruit cause a net like russeting and disfiguring of the fruit. Infections lead to smaller, distorted fruit leading to reduction of fruit yield and quality. Fruit trees with heavy levels of infection become weakened and are more prone to infections from other pathogens. Control recommendations are the planting of resistant cultivars, removal of infected plant tissues from the orchard to avoid reinoculation, and foliar fungicide applications. Susceptible cultivars may require as many as eighteen sprays per season for adequate control (Marine, S.C. et al., 2010).

Sooty blotch/Flyspeck is a fungal community that colonizes the waxy layers of apples. This colonization does not damage the tissues below but causes the fruit to develop unsightly blemishes which leads to the downgrading of the fruit, and economic loss. Sooty blotch/flyspeck infections can cause a loss of valuation of up to ninety percent in high value cultivars in eastern North America. (Gleason et al., 2011). To control Sooty blotch/Flyspeck it is recommended to prune the canopy, which lowers the humidity making it less hospitable for the growth of fungi. Biological and chemical anti-fungal foliar applications are also recommended, as well as post-harvest dips to stop the growth of sooty blotch/flyspeck in storage (Williamson et al., 2000).

Bitter pit is a disease characterized by dark, corky, depressed spots on the surface of the apple due to calcium deficiency. Cellular structure and function are reliant on calcium, the disorder leads to water-soaked symptoms caused by the breakdown of the plasma membrane followed by dehydration and tissue disintegration (de Freitas et al., 2010). Causative conditions of bitter pit can be low soil pH, boron deficiency, drought, and/or excessive tree vigor and fruit size (Rosenberger et al., 2004). To control bitter pit, it is recommended that high levels of calcium chloride are applied throughout the summer, however these applications alone may be ineffective if crop load, fruit size, or thinning have predisposed fruit to bitter pit conditions (Biggs et al., 2015).

Treating common arthropod pests in Michigan high density apple orchards requires dealing with direct and indirect arthropod pests that cause damage to both fruit and foliage. Common arthropod pests include: Aphids (Hemiptera: Aphididae), apple maggot, Rhagoletis *pomonella* (Walsh), Japanese beetle, *Popillia japonica,* Walsh, leafhoppers (Hemiptera: Cicadellidae), Latreille, mites (Arachnida:Trombidiformes), plum curculio, *Conotrachelus nenuphar,* (Herbst) , San jose scale, *Quadraspidiotus perniciosus,* Comstock, sucking hemipterans (Hemiptera:Heteroptera), and tortricid moths (Lepidoptera:Tortricidae).

Common aphid pests in Michigan apple orchards include green apple aphid, *Aphis pomi* (de Geer), rosy apple aphid, *Dysaphis plantaginea* (Passerini), and wooly apple aphid, Eriosoma lanigerum (Hausmann). Both green and rosy apple aphids overwinter in the egg and hatch around the same time in the spring. Wooly apple aphids overwinter as eggs or as nymphs underground on apple roots if elm trees are not available. All three species feed on sap within plant tissues causing leaves to curl and can also lead to the malformation of fruit, making it unsalable. Aphid excrement known as “honeydew”, which is a byproduct of sap feeding, accumulates with large aphid populations and promotes the growth of fungal pathogens. Wooly apple aphid differs from rosy and green apple aphid as they cover themselves with a waxy fibrous covering as well as feed below ground. Wooly apple aphids do the majority of their damage underground, just above the root which can lead to root decay. Increased aphid populations can be attributed to cool wet springs limiting natural predators, and untrimmed trees, which provide safe haven and hinder control methods. Control methods include pruning the canopy as well as the use of contact or systemic aphicides beginning at pre blossom. Early applications are most effective as they allow for compounds to reach aphids before they have the ability to take refuge in curled leaves. Pesticide usage can lead to increased aphid numbers as it also eliminates insects that predate on aphids. (Howitt, 1993). Some recommended treatments include but are not limited to applications of Carbamates, Sulfoximines, Neonicotinoids, Diamides, as well as alternative, softer chemistries like potassium salts of fatty acids, etc. (Wise et al., 2022).

Apple maggot is a species of fly, whose larva tunnel through apple flesh, softening the fruit leading to its decay. Females puncture immature fruit and lay eggs, the eggs hatch and develop into larvae who burrow through the apple. The puncture site often becomes a sunken dimple as damaged tissues do not grow with the rest of the apple. Mature larvae leave the fruit and enter the soil where they enter the pupal stage. Adults emerge the following summer from late June to early September. Successful control is based primarily on killing the flies before the females have a chance to oviposit. This 8-to-10-day window is known as the pre-oviposition period which takes place after adults emerge from the soil. During this pre oviposition period adult females and males rest and feed with little to no interest in fruit. Monitoring with yellow sticky traps and baited red plastic balls for oviposition activity allows for the proper timing of an insecticidal spray (Howitt, 1993). Recommended control of apple maggot includes but is not limited to applications of organophosphates, neonicotinoids, spinosyns, diamides, and bacterial based biopesticides etc. (Wise et al., 2022).

Japanese beetles are most active from June to September in mating clusters on host plants post emergence. Control can be a challenge as the beetles are strong flyers and can feed on more than 300 species of plant (Wise et al. 2007). Females lay eggs in the soil with the larva overwintering until their emergence in the summer as adults. When temperatures reach ~70°F beetles are most active and will consume foliage or fruit, with a preference for ripening or diseased fruit. Protection of fruit and foliage can be achieved by hanging aggregation pheromones and traps for detection and spraying insecticides when beetles first appear. (Howitt, 1993). Applications of organophosphates, carbamates, and neonicotinoids are recommended to control Japanese beetle infestations ect. (Wise et al., 2022).

White apple leafhopper, *Typhlocyba pomaria,* McAtee feeds on both the foliage and fruit of the apple tree. The first generation overwinters as eggs beneath the bark and the second as eggs laid on the underside of leaves. The first-generation nymphs feed on chlorophyll leaving white streaks or spotting on leaf surfaces, heavy feeding can cause the entire tree to appear this way. This damage can affect fruit quality and the formation of buds if feeding occurs early enough in the season. Spotting and streaking on fruit is caused by an accumulation of leafhopper waste produced by the second generation. Control of leafhoppers can be difficult due to their tendency to occupy the underside of leaves, shielded from spray applications and quick development of pesticide resistance. Thorough Coverage of both top and bottom of foliage with effective chemistry is essential for control (Howitt, 1993). Applications of pyrethroids and neonicotinoids are recommended to control leafhoppers, as well as oxadiazines (indoxacarb) and chitin biosynthesis inhibitors (buprofezin) etc. (Wise et al., 2022).

European red mites, *Panonychus ulmi*, (Koch), Apple rust mites, *Aculus schlechtendali*, (Nalepa) and two spotted spider mites, *Tetranychus urticae*, (Koch) are pests of apples in Michigan orchards. All three species feed by inserting their mouth parts into plant cells and consuming their contents. This feeding gives the underside of leaves a brown or bronzed color. European red mite eggs overwinter with the condition of the tree at the end of the season determining the number of eggs left to overwinter. Trees heavily damaged in midsummer by a large red mite population will leave few eggs behind as resources were expended and high numbers of predators have reduced the population. The opposite is true for trees with lower population levels and the following year will have larger infestations earlier in the season. Serious infections by the two spotted spider mite leaves similar signs of damage to foliage as the European red mite with the difference being a more grayish tone to affected leaves. Also, a silken web may be spun over infested leaves. The apple rust mite is rarely seen as a pest and is actually known to be beneficial as it feeds mite predators early in the season before more damaging mite populations develop. Predacious mites can effectively suppress pest mites, as long as they are not harmed by treatments of broad-spectrum insecticides. Applications of miticides are recommended for controlling mite infestations (Howitt, 1993). Treatments to control European red mite are recommended to begin at tight cluster with applications of superior oil and mite growth inhibitors affecting chitin synthase 1 (Clofentezine, Diflovidazin, Hexythiazox), ect. Treatments to control apple rust mite are recommended to begin at first cover with applications of mite growth inhibitors affecting chitin synthase 1 (Clofentezine, Diflovidazin, Hexythiazox), METI acaricides (e.g., Fenazaquin, Pyridabin), and inhibitors of Acetyl COA carboxylase (tetroinic and tetramic acid derivatives), etc. Treatment of two spotted spider mite is recommended to begin at third cover with applications of Beta-ketonitrile derivatives (e.g., Cyenopyrafen), pyrethrins, pyrethroids, carbamates, etc. (Wise et al., 2022).

Plum curculio is a beetle that causes damage to apples at multiple points in its lifecycle. First an adult female cuts a cavity under the skin of a developing apple, then proceeds to cut a crescent shaped slit under the cavity, sliding the egg into the cavity. This crescent shaped scar remaining at harvest is a sign that the egg did not hatch and develop into larva. If the larva hatches it will burrow through the fruit, to its core, feeding until maturity with a majority of the infected fruit dropping in June. After apple drop larvae make their way into the soil, construct a pupal cell, and in approximately thirty days time emerge as an adult. As an adult it will continue damaging apples as it feeds, until cold weather where it will seek shelter for hibernation. Monitoring for plum curculio is performed by beating tray, by dislodging adults from the foliage during the early morning of petal fall. Assessing fruit for adult feeding and oviposition injury can also signal the presence of plum curculio in the orchard. To control plum curculio at petal-fall, first cover (7-10 days after petal fall), and second cover (7-10 days after first cover) sprays of an insecticide are recommended, intended to disrupt adult oviposition. This pest is considered difficult to control and full dosages of effective pesticide are recommended (Howitt 1993). Treatments to control plum curculio are recommended to begin at petal fall with applications of pyrethrins, pyrethroids, diamides, organophosphates, oxadiazines, neonicotinoids, etc. (Wise et al., 2022).

San Jose scale feeds on the sap of the host plant it has infested. The pest is so prolific that just a few pairs can be responsible for millions of progeny in a season or two, this leading to complete coverage of the host by San Jose Scale, a single female can produce more than 300 million per year. As this is an invasive species it lacks adequate predation to control its numbers, becoming so prolific it is able to kill a shrub in just a few years, even older trees cannot withstand the prolific feeding of so many individuals. Feeding is not limited to the bark but will also infest leaves and fruit, sign of scale on fruit is a red spot, with infestations making the fruit unmarketable. Crawlers, younger forms of the insect can be spread by wind, wildlife, farm implements, and the clothes of those who've made contact with an infected tree. Scale may go undetected until it has infested fruit due to its small size. In order to detect scale pheromone traps can be placed to capture winged males during bloom and petal fall, along with sticky traps to detect the crawling phase of the insects life cycle. Control can be achieved by the application of superior oil during pre bloom. Insecticide applied at early petal fall will control males before they are able to mate, as well as crawlers with adequate coverage (Howitt 1993). Applications to control San Jose scale, are recommended to begin at tight cluster, applying organophosphates, butenolides, superior oil, juvenile hormone mimics (Pyriproxyfen), etc. Insecticide applications are recommended to begin at pink and crawler stage using pyriproxyfen, butenolids, benzoylureas, ect. (Wise et al., 2022).

Sucking hemipterans like Tarnished Plant Bug, *Lygus lineolaris*, (Palisot de Beauvois), and Brown Marmorated Stink Bug (BMSB), *Halyomorpha halys*, Stål both feed on plant sap inserting feeding mouthparts into plant tissues. Results from feeding in apples range from discoloration to disfiguration, making fruit unmarketable. In spring tarnished plant bugs lay eggs in blossom buds, causing damage near the calyx. Control of tarnished plant bug is considered difficult as it migrates from outside of the orchard and should be controlled by spraying at the pink stage (Howett 1993). Brown marmorated stink bugs lay eggs on the bottom side of leaves, of a chosen host plant. As the nymphs reach adulthood in early to late August, they become a greater threat to orchards as large populations begin aggregating. Apples are listed in the moderate to high-risk group for Michigan with nymphs appearing as early as June. Both adults and nymphs can cause damage to apples but may not be detectable until months later. Damage from BMSB can appear similar to tarnished plant bug. Orchards near woodlots are considered at highest risk for a Brown marmorated stink bug invasion. Traps should be set to confirm the presence of BMSB in the orchard. Insecticidal sprays are recommended for control (Wilson et al., 2020). Treatments to control tarnished plant bug are recommended to begin at pink stage with applications of carbamates, pyrethroids, pyrethrins, and flonicamid (Wise et al., 2022). Treatments to control BMSB are recommended to begin at sixth cover with applications of carbamates, pyrethroids, pyrethrins, neonicotinoids, etc. (Wise et al., 2022).

Tortricid moths like the Oriental fruit moth, *Grapholita molesta*, (Busck) and the Codling moth *Cydia pomonella*, (L.) are internal feeders, their larva developing inside growing fruit. Moths like the Oblique banded leafroller, *Choristoneura rosaceana*, (Harris) damage the surface of the fruit. Both oriental fruit moth and codling moth are similar in the way they cause damage to apples. Eggs are laid near the developing apple, the larva makes its way into the apple where it feeds, damaging apple tissues. Two types of damage are caused by larva, stings and deep entries. Stings are shallow holes bored where the larva died and failed at entry into the fruit. Deep entries are where the larva have penetrated the fruit, from either the side or calyx end, leading to significant damage. Successful larvae will feed inside the apple for about three weeks at which point it will cocoon itself on the trunk or branches of the tree. After 14 to 21 days depending on temperature and rainfall an adult moth will emerge. While their damage and larva look similar, the way to differentiate oriental fruit moth larva from codling moth larva is the presence of an anal comb on the posterior end of the oriental fruit moth larva. Pheromone-baited traps are recommended to confirm the presence of codling moth, or oriental fruit moth in the orchard, as effective treatment requires larva to be exposed to pesticide before making entry into the apple (Howitt 1993). To control oriental fruit moth, use of mating disruption pheromones are recommended beginning at pink stage. Insecticides applications are recommended to begin at petal fall using carbamates, organophosphates, pyrethrins, pyrethroids, diamides, spinosyns, etc. To control codling moth mating disruption pheromones are recommended beginning at bloom.

Obliquebanded leafroller feeds on both foliage and fruit. They begin hatching out in bud clusters where they feed on parts of the flower and developing leaf tissue. After petal fall they begin feeding on fruit and growing leaves. At this point they begin to feed on the surface of apples leaving deep gouges. Pupation occurs at the site of feeding, lasting 10 to 12 days, moths emerging mid-June to mid-July. Broad spectrum insecticides applied at pink or petal fall are recommended to control damage from overwintering larvae. Summer sprays are recommended to be timed with the presence of leaf rollers in traps (Howitt 1993). Treatments to control obliquebanded leafroller are recommended to begin at pink stage with applications of pyrethroids, diamides, IGRs, spinosyns, etc. (Wise et al., 2022).

Other agrochemicals are applied to the orchard aside from those used to control pests. For example, nutritional and thinning agents are often applied as foliar treatments. Foliar nutrients are often sprayed to maintain plant health, prevent disorders, and improve fruit quality. Foliar applications are optimal for delivering all sources of plant nutrients and pose the lowest risk of soil and groundwater contamination (Murtic et al., 2012). Fruit thinning is the practice of reducing the number of fruit per tree. The reduction of the number of apples per tree protects tree limbs from breaking due to fruit load, prevents losses of tree reserves, and allows for larger higher quality apples. Chemical thinning is achieved by applying compounds that disrupt the formation of, or prevent apples from reaching maturity. For example, naphthalene acetic acid (NAA) is a plant bioregulator that when applied after bloom reduces fruit set. The insecticide carbaryl (1-naphthyl-N-methylcarbamate) is regarded as a mild thinning agent and is recommended to be used with NAA in difficult to thin varieties (Dennis, 2000).

Previous experiments involving Solid Set Canopy Delivery Systems demonstrate not only the technology’s ability to reduce off-target drift but to also provide comparable coverage to the leaf surface, produce higher deposition, and comparable year-long pest management when compared to a fan-assisted orchard sprayer (Angello, & Landers, 2006; Sinha et al. 2019; Owen-Smith et al. 2019; Sanhi et al. 2022). What has yet to be determined is to combine coverage, deposition, pest management, and fruit quality measurements across multiple varieties of apple treated by the SSCDS. This experiment also includes a new emitter configuration, the above canopy SSCDS, that removes emitters from within the canopy.

I hypothesized in canopy SSCDS coverage and deposition values will be similar in differing strata within the canopy. I hypothesized that above canopy SSCDS deposition and coverage values will be highest at the top of the canopy and coverage will be highest on the adaxial face of spraycards. I also hypothesized that the above canopy SSCDS, in canopy SSCDS, and an Airblast axial-fan sprayer will provide equivalent pest management. Along with pest management I hypothesized that fruit quality will be equivalent among the above canopy SSCDS, in canopy SSCDS, and Airblast.

3.2. Materials and Methods

To meet the experimental objectives, two years of pest management efficacy evaluations were conducted. The experiment was composed of three treatments, above canopy SSCDS, in canopy SSCDS and a Rears PB533N Radial Airblast sprayer, known as the Airblast (Rears Manufacturing company, Coburg, OR, USA) in a high density apple orchard. In canopy and above canopy SSCDS coverage and deposition were evaluated August of 2019, as were the incidence of clean fruit and foliage and insect and disease damaged fruit and foliage. In August of 2020 I measured incidence of clean fruit and foliage, insect disease damaged fruit and foliage as well as fruit quality measures of apple weight, apple size, apples per tree, and apples per hectare.

Experiment Site. Coverage, deposition, pest management, and fruit quality evaluations were conducted in a high-density orchard at the Michigan State University Clarksville Research Center Clarksville, Michigan, United States (42.873933081589804, -85.25857635397287). The treated area consisted of 6 0.20 hectare plots; each plot contained fifteen 38.1 meter long rows of densely planted Gala, Honeycrisp, and Fuji varieties of apple trees; each variety occupied five rows each. Apple cultivars were Buckeye Gala on bud 9 rootstock, Royal Red Honeycrisp on M9-337 rootstock and Aztec Fuji on M9-377 rootstock. Trees were approximately 2.5 m tall with 0.91m spacing between trees, with forty-five trees per row and 3.66 m row spacing. Tree rows were planted lengthwise, latitudinally (North/South) in Spring of 2017.

Experimental design. This experiment was conducted as a complete block design, with three plots dedicated to treatment from the in canopy and above canopy SSCDS and three plots adjacent treated by the Airblast sprayer. The SSCDS treated blocks were split perpendicular to the orchard rows with half of the plot treated by the in-canopy SSCDS and half the plot by the above-canopy SSCDS. The SSCDS half plots were also split East/West with eight rows to the east controlled separately from the seven to the west this allowed for greater pressure control

(Figure 3.2). Splitting the orchard plots created 60 m orchard rows placing an in canopy and above canopy SSCDS in each apple variety, with a 5 m buffer in the center with no emitters, preventing areas from receiving overlapping treatment from both systems (Figure 3.1). The remainder of the orchard plots were treated by the Airblast sprayer, serving as a positive control.

Past experiments in the surrounding orchard blocks provided background pest pressure so an untreated control was not assessed during this experiment. Untreated controls assessed by Owen-Smith (2019) detected ~80% scab damaged fruit along with ~30% of the fruit damaged by external feeding arthropods and ~20% of the fruit damaged by internally feeding arthropods. Similar findings in the same orchard by Grieshop (2019) detected > 90% of the apples treated conventionally free of arthropod and disease damage. In the same orchard a failed treatment, detected no pest management with the percentage of clean fruit at highest ~50%.

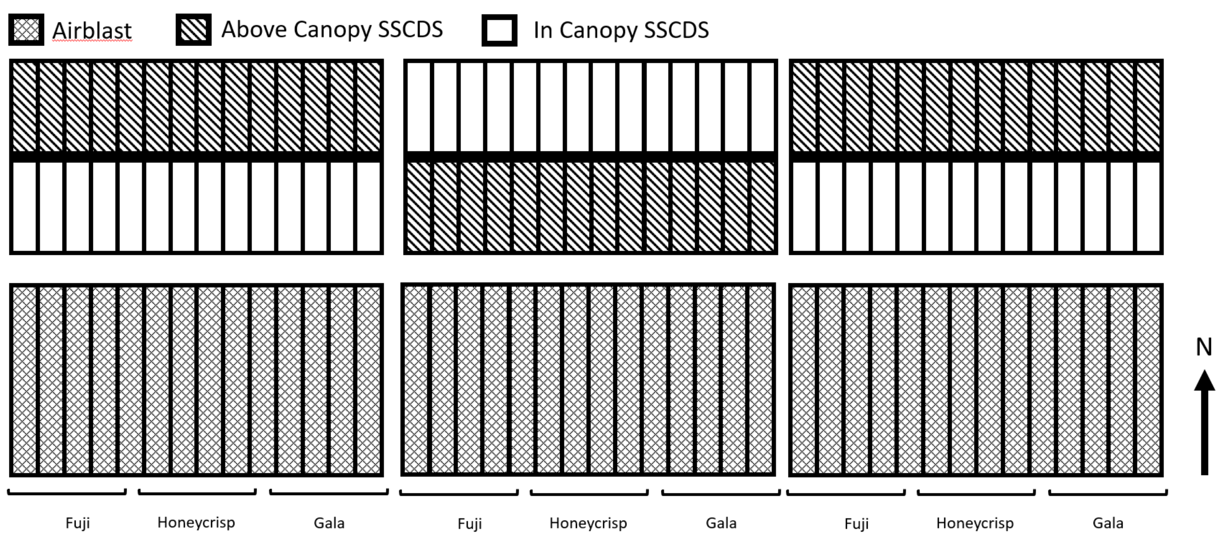

Figure 3.1- Experimental site plots treated by both SSCDS configurations and Airblast. Six 0.2 ha orchard plots with three apple varieties, five rows each. Three plots were treated by Rears Airblast and three split in the center one half treated by the above canopy and the other the in canopy SSCDS.

SSCDS Design. The SSCDS designs used in these experiments were based on a design described in Owen-Smith et al. (2019). The basic form of an SSCDS used a hydraulic pump fed from a holding tank driving liquid through irrigation lines plumbed to micro-emitters. The systems evaluated in my experiments consisted of 2.54 cm diameter polyethylene irrigation tube (Toro, Bloomington, Minnesota, USA) hung at the top (2.5 m) of each orchard row, referred to as the application line (Figure 3.2 A). Micro-emitters were plumbed into the application lines via 220.63 kPa leak prevention devices (Jain irrigation, Jalgaon, Maharashtra, India). My system, differing from (Owen-Smith et al.) 2019 was constructed with 5.08 cm diameter “Tigerflex” spa tube (Kuriyama Inc., Schaumburg, IL, USA) which fed the application lines, referred to as a feed line (Figure 3.2 B. These feed lines were attached to a Honda GX 160 water pump (Honda, Minato City, Tokyo, Japan) and ran perpendicular to the orchard rows and attached to every other application line. Application lines not attached to the feed line were attached to a 2.54 cm diameter polyethylene irrigation tube known as the return line (Figure 3.2 C) that returned material back to a 956.4 L reservoir tank (Norwesco, St. Bonifacius, Minnesota, USA).

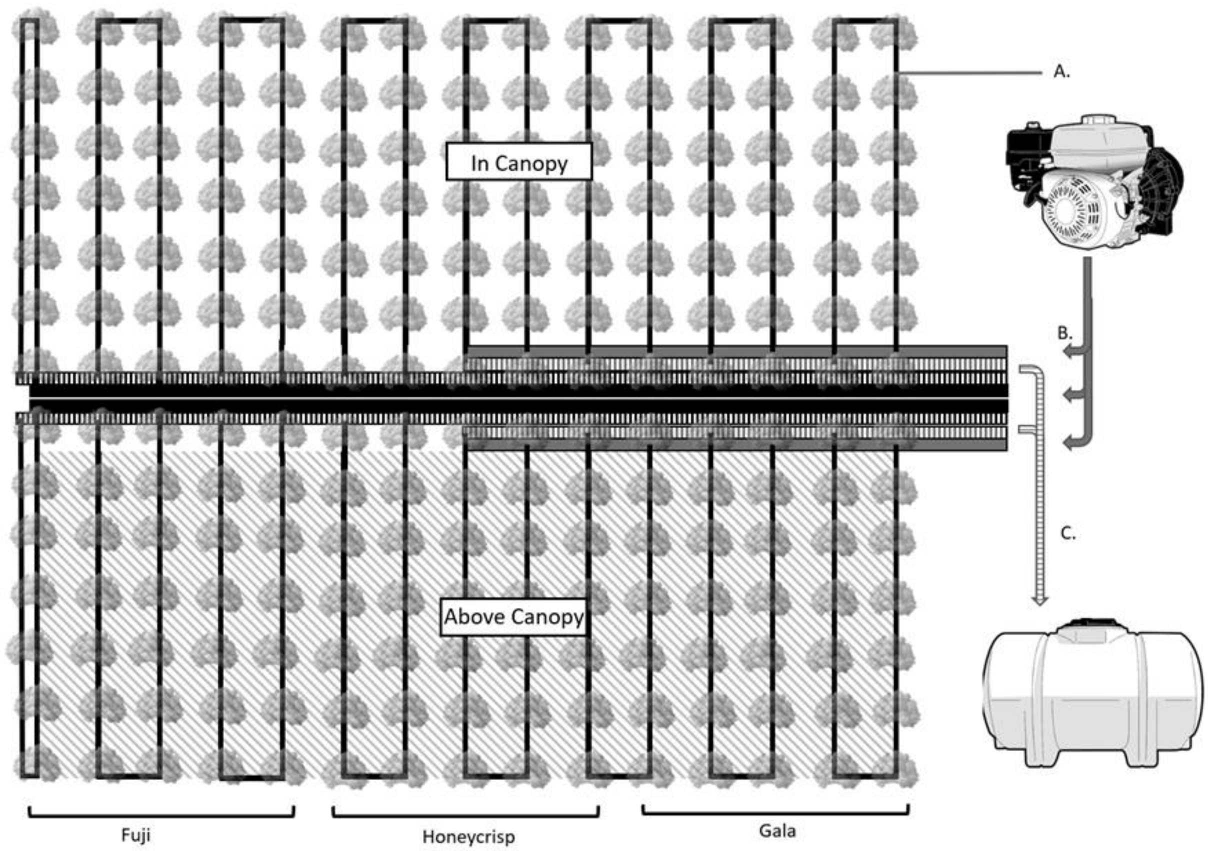

Figure 3.2 - SSCDS plot configuration. Plots were split between the above canopy and in canopy SSCDS. Application lines carried agrochemical to the emitters and attached to both the feed lines and return lines (A.). Solid lines in the center of the plot were “feed lines” pushing agrochemical from tank to the application lines (B.) Stripped lines are return lines and carried agrochemical from the application lines back to the holding tank (C.).

SSCDS Configurations. The in-canopy SSCDS configuration that was used for this experiment was the same as described in Koonter (2023). In canopy SSCDS emitters consisted of a Jain 7110 bridge with Jain 3044 impactors (Jain irrigation, Jalgaon, Maharashtra, India) with a flow rate of 0.56 lpm with one emitter at the top of the canopy (2.5 m above ground) and a pair mid canopy (0.9 m above ground). Each triplet of emitters was controlled by a Jain 220.63 kPa leak prevention device plumbed into the delivery line.

Each above canopy SSCDS emitter consisted of a Jain 7110 bridge and Jain green nozzle with a flowrate of 1.14 lpm. These emitters were fitted with 3D printed impactors as described by Ranjan (2021). These impactors were designed with fifty-degree deflection angles and produced a wetted diameter of 3 m when emitters were located 2.5 m above ground. Emitters were placed above the canopy 2.5 m above ground and placed every 0.94 m with every two emitters controlled by the same Jain leak prevention device as the in canopy SSCDS, placed every 1.83 m.

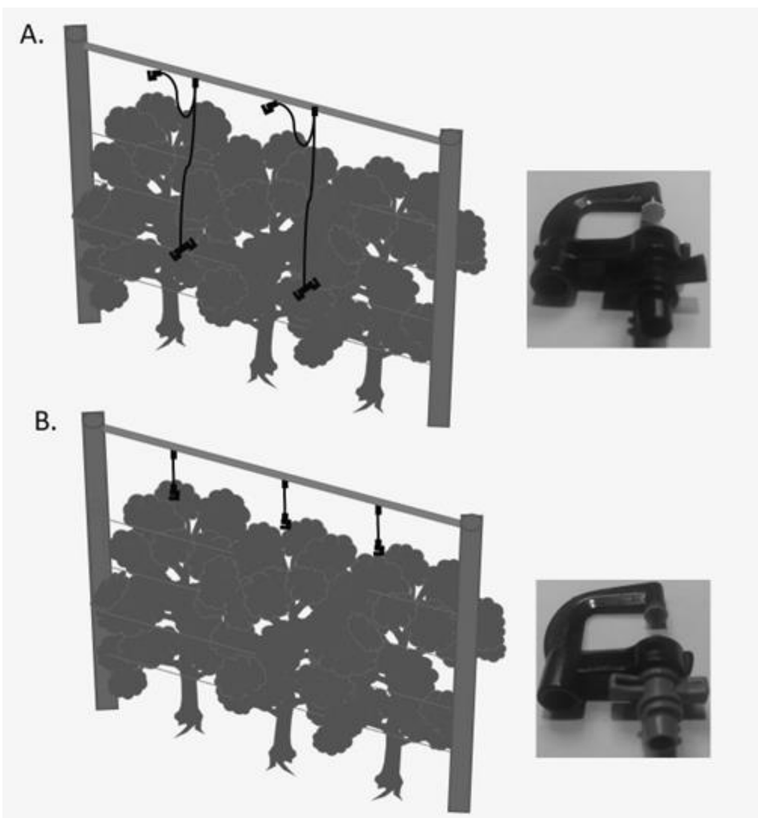

Figure 3.3 - In canopy and above canopy SSCDS emitter placement. In canopy SSCDS (A.) 7110 body 3044 impactor, single emitter at top of canopy and pair in the center of the canopy. Above canopy SSCDS (B.) 7110 body custom 50-degree impactor, single emitters above the canopy.

Agrochemical Application (SSCDS and Airblast). The SSCDS system operated in three phases. The first phase was the low pressure (<220.63 kPa) filling phase where the entire system was filled from the holding tank. The second phase was the application phase, where the system pressure was increased to ~ 344.74 kPa opening the leak prevention devices and passing agrochemical to the emitters for application. The third phase was the return phase where pressurized air from an industrial air compressor was fed into the system at a lower pressure than the opening pressure of the leak prevention devices (<220.63 kPa) pushing all liquid remaining in the lines back to the holding tank.

The target application rate for the in-canopy SSCDS, above-canopy SSCDS and Airblast sprayer for determining coverage, deposition and pest management applications was 467.7 l/ha. The application rate for the SSCDS is controlled by time of application. In order to achieve this application rate, the in-canopy SSCDS was activated for 11 seconds and the above-canopy SSCDS was operated for 8 seconds. The Rears PB533N Airblast sprayer was fitted with Teejet DC23 hollow cone, ceramic discs and whirl plates (Teejet Technologies, Glendale Heights, IL, USA) and applied to every row at the same field rate as the SSCDS configurations (467.7 l/ha).

Coverage and Deposition. Weather data was recorded via the Enviroweather system located at the Clarksville Research Center. Weather conditions recorded were as follows: Temperature ºC, Relative Humidity, Wind Speed minimum, Wind Speed maximum, Wind speed average. (Table 3.3)

Coverage and deposition provided by the in-canopy and above-canopy SSCDS was measured using of 10.16 cm × 2.54 cm water sensitive paper (Teejet Technologies, Glendale Heights, IL, USA) and 10.16 cm × 10.16 cm mylar cards (Grafix, Cleveland, Ohio, USA) respectively. To determine both coverage and deposition at the time of application a mixture of 0.1% m/v Keystone pyranine 10G dye (Keystone Inc., Chicago, Illinois, USA), 0.1% v/v commercially available non-ionic surfactant (Ragan & Massey Inc., Ponchatoula, Louisiana, USA) and water was applied to the orchard. At each application a 20 ml tank sample was collected for the development of a calibration curve. This pyranine mixture acted as an agrochemical surrogate for quantification of deposition made to the mylar cards and also reacted with the water sensitive paper, allowing for the quantifying of coverage.

Water sensitive paper and mylar cards were placed in the top, middle, and bottom third of the orchard canopy in the east and west sides of three trees located in the center row of each variety (Gala, Honeycrisp, Fuji) for each treatment (above canopy, in canopy) in each of the three blocks used. At each water sensitive paper location, two pieces of water sensitive paper were placed, one facing upward (adaxial) and one facing the ground (abaxial) simulating the upper and underside of leaves.

Individual water sensitive papers and mylar cards were collected with gloved hands and placed in 20 × 12 cm 6 mil plastic bags (US Plastics, Lima, Ohio, USA) after each treatment. Both water sensitive paper and mylar cards were stored in a cooler of dry ice buffered by heavy canvas. Water sensitive paper was stored in a dark, cool, and dry place until processing. Mylar cards were stored in a –20ºC freezer until time of processing.

Coverage: Water Sensitive Paper. Water sensitive papers were scanned at 4800 dots per inch using a Canon photo quality flatbed scanner (Canon Inc., Arlington, VA, USA). The imaging software ImageJ (Fiji Software) first thresholded images of the water sensitive paper then analyzed them for percent coverage based on the color difference displayed by the surfaces of the cards with exposure to moisture.

Deposition: Tank sample curve. Detection procedures were based on previous publications (Khot et al. 2012 & Salyani et al. 2000). A calibration curve was developed by tank samples collected for each application. Tank samples were initially diluted by 50% with a mixture of 10%v/v isopropyl alcohol/distilled water solution and then serially diluted by factors of 10, 100, 1000, 10,000 and 100,000 which corresponded to 0.5 g L^{-1}, 0.05 g L^{-1}, 0.005 g L^{-1}, 0.0005 g L^{-1}, 0.00005 g L^{-1} , respectively. Each one of these dilutions was added to three sequential chambers of a Trueline TR5002 24 well plate (Corning Inc., Corning, NY, USA), then analyzed with the Biotek Synergy HT spectrophotometer, excitation 400/30 nm and emission 540/25 nm (BIOTEK, Winooski, VT, USA). The three sequential wells relative fluorescence units were averaged, and the resulting number equaled an average of relative fluorescence units. Fluorescence values from the tank samples were used to create a nonlinear equation for each spray application that were then used to calculate the mass of pyranine deposition to mylar cards in grams per centimeter squared.

Deposition: Dye release. To release the dye from the mylar cards, the cards in their bags were thawed and 10 ml of a 10% v/v of 90% isopropyl alcohol mixture in distilled water was added to the bags. Bags were agitated, and all surfaces of the card were exposed to the mixture to ensure the release of the dye from the mylar card.

Deposition: Dye detection. To detect the fluorescence of the pyranine deposited to the mylar cards, 6 ml of the dye and release agent in the bags was pipetted in 2 ml aliquots into three sequential chambers of a Trueline TR5002 24 well plate. Using the spectrophotometer methods described above for the tank samples, three sequential wells were used to generate an average of relative fluorescence units or RFU per sample. Using the calibration curve produced by the fluorescent dye dilutions from each independent tank sample, each drift sample was converted from RFU's (reflectance units) to grams per centimeter squared. This value was converted to percent flux as a proportion of the applied rate assuming 100% deposition based on Fritz et al. (2008).

Pest management. Pest management for 2019 and 2020 was provided by the above canopy SSCDS, in canopy SSCDS and Rears Airblast sprayer. In 2019, the above-canopy and in-canopy SSCDS began treatments on 6/20/2019 once system installation was complete. From 4/10/2019 to 6/12/2019 the Airblast provided agrochemical applications to the entire orchard including the SSCDS blocks. The number of applications made by the above canopy SSCDS, in canopy SSCDS, and Airblast were equivalent in 2020. Applications were made by all three treatments on the same day, using the same products, and at the same rate. SSCDS application rates were controlled by time, the above canopy SSCDS emitters applied at a rate of 0.56 l/m and were active for 11 s, the above canopy SSCDS emitters applied at a rate of 1.14 l/m and were active for 8 s. SSCDS applications were mixed with water in a 956.4 L tank. All treatments were (above canopy SSCDS, in canopy SSCDS, Airblast) applied at a rate of 467.70 l/ha.

Table 3.1 - 2019 Applications of agrochemical to the orchard. Date, product name, active ingredient, type, Formulation, and amount per hectare of applications made to the orchard by above canopy SSCDS, in canopy SSCDS, and Airblast in 2019.

Date	Product	Active Ingredient	Type	Formulation	Rate/ha
4/10	COC DF	copper oxychloride	Fungicide	DF	4.4 kg
4/19	Roper	mancozeb	Fungicide	WDG	3.36 kg
4/19	Vangard	cyprodinil	Fungicide	WDG	0.35 kg
4/25	Aprovia	benzovindiflupyr	Fungicide	EC	501.31 ml
4/25	Sivanto Prime L	flupyradifurone	Insecticide	EC	667.93 ml
5/2	Roper	mancozeb	Fungicide	WDG	3.36 kg
5/2	Merivon	fluxapyroxad + pyraclostrobin	Fungicide	SC	292.31 ml
5/10	Roper	mancozeb	Fungicide	WDG	3.36 kg
5/10	Vangard	cyprodinil	Fungicide	WDG	0.35 kg
5/10	Anarchy	acetamiprid	Insecticide	SG	0.16 kg
5/17	Omega	fluazinam	Fungicide	F	935.40 ml
5/17	Sonata	*Bacillus pumilis*	Fungicide	SC	6664.69 ml
5/17	FireWall	streptomycin sulfate	Fungicide/ Bactericide	WP	1.12 kg
5/17	FireLine	oxytetracycline	Fungicide/ Bactericide	WP	1.12 kg

Table 3.1 (cont'd)

5/24	Fortuna	mancozeb	Fungicide	WDG	6.73 kg
5/24	Indar	fenbuconazole	Fungicide	F	438.47 ml
5/24	Kasumin	kasugamycin	Fungicide/ Bactericide	L	4676.98 ml
5/29	Belay	clothianidin	Insecticide	SL	438.47 ml
5/29	Merivon	fluxapyroxad + pyraclostrobin	Fungicide	SC	350.77 ml
5/31	PoMaxa	1-Naphthalene Acetic Acid	fruit thinning	L	146.16 ml
5/31	Sevin XLR Plus	carbaryl	fruit thinning	F	1169.24 ml
6/7	PoMaxa	1-Naphthalene Acetic Acid	fruit thinning	L	456.74 ml
6/7	Sevin XLR Plus	carbaryl	fruit thinning	F	584.62 ml
6/12	Omega	fluazinam	Fungicide	F	935.40 ml
6/12	Delegate	spinetoram	Insecticide	WDG	0.42 kg
6/20	Omega	fluazinam	Fungicide	F	935.40 ml
6/20	Movento	spirotetramat	Insecticide	SC	657.7 ml
6/27	Voliam Flexi	chlorantraniliprole + thiamethoxam	Insecticide	WDG	0.47 kg
6/27	Luna Sensation	fluopyram + trifloxystrobin	Fungicide	SC	365.39 ml
7/4	Movento	spirotetramat	Insecticide	SC	657.7 ml
7/23	Indar	fenbuconazole	Fungicide	F	584.62 ml
8/9	Anarchy	acetamiprid	Insecticide	SG	0.56 kg
8/9	Incognito	thiophanate-methyl	Fungicide	WDG	0.77 kg
8/23	Assail	acetamiprid	Insecticide	SG	0.56 kg
8/23	Incognito	thiophanate-methyl	Fungicide	WDG	0.77 kg
9/4	Exirel	cyantraniliprole	Insecticide	SC	1039.17 ml
9/4	Incognito	thiophanate-methyl	Fungicide	WDG	0.77 kg

Table 3.2- 2020 Applications of agrochemical to the orchard. Date, product name, active ingredient, type, formulation, and amount per hectare of applications made to the orchard by above canopy SSCDS, in canopy SSCDS, and Airblast in 2020.

Date	Product	Active Ingredient	Type	Formulation	Rate/ha
4/22	fortuna	mancozeb	Fungicide	WDG	3.36 kg
4/22	approvia	Benzovindiflupyr	Fungicide	EC	438.47 ml
4/22	zinc 7%	zinc	Fungicide	WP	4676.98 ml
4/30	penncozeb	mancozeb	Fungicide	DF	3.36 kg
4/30	inspire super	Difenoconazole + Cyprodinil	Fungicide	EW	0.84 kg
5/8	omega	fluazinam	Fungicide	EC	935.40 ml

Table 3.2 (cont'd)

5/13	mervion	Fluxapyroxad + pyraclostrobin	Fungicide	EC	365.39 ml
5/23	flint extra	Trifloxystrobin	Fungicide	EC	166.62 ml
5/23	omega	fluazinam	Fungicide	EC	935.40 ml
5/23	kasumin 2L	kasugamycin	Fungicide/Bactericide	L	4676.98 ml
5/25	kasumin 2L	kasugamycin	Fungicide/Bactericide	L	4676.98 ml
5/27	agri-mycin 17	streptomycin	Fungicide/Bactericide	WP	1.12 kg
5/27	mycoshield	oxytetracycline	Fungicide/Bactericide	WP	1.12 kg
5/28	omega 500F	Fluazinam	Fungicide	EC	935.40 ml
5/28	belay	Clothianidin	Insecticide	EC	438.47 ml
5/28	aprovia	Benzovindiflupyr	Fungicide	EC	467.70 ml
6/1	Sevin XLR plus	carbaryl	Thinning	EC	2338.50 ml
6/1	PoMaxa	1-Naphthalene Acetic Acid	Thinning	L	292.31 ml
6/8	mervion	Fluxapyroxad + pyraclostrobin	Fungicide	EC	365.39 ml
6/8	voliam Flexi	Thiamethoxam + Chlorantraniliprole	Insecticide	WDG	935.40 ml
6/26	voliam Flexi	Thiamethoxam+ Chlorantraniliprole	Insecticide	WDG	935.40 ml
6/26	Luna sensation	Fluopyram + Trifloxystrobin	Fungicide	SC	730.78 ml
7/6	Endivor	Spirodiclofen	Acaricide, Insecticide	SC	1315.40 ml
7/6	movento	Spirotetramat	Insecticide	SC	657.7 ml
7/6	inspire super	Difenoconazole + Cyprodinil	Fungicide	EW	876.93 ml
7/6	prey	Imidacloprid	Insecticide	EC	292.31 ml
7/6	Rainier	Polyoxyethylene polyol fatty acid ester, butyl lactate, alcohol ethoxylate phosphate ester	Surfactant	EC	2338.50 ml

Table 3.2 (cont'd)

7/17	anarchy	Acetamiprid	Insecticide	WSG	0.56 kg
7/17	Rainier	Polyoxyethylene polyol fatty acid ester, butyl lactate, alcohol ethoxylate phosphate ester	Surfactant	EC	935.40 ml
7/31	anarchy	Acetamiprid	Insecticide	WSG	0.56 kg
7/31	incognito	Thiophanate-methyl	Fungicide	L	0.56 kg
8/19	belay	Clothianidin	Insecticide	EC	438.47 ml
8/19	Indar	fenbuconazole	Fungicide	EC	0.56 kg
9/3	incognito	Thiophanate-methyl	Fungicide	WDG	0.897 kg

Foliar and fruit damage assessment. Fruit and foliar damage were evaluated in summer and fall in 2019 and 2020. Mid-season assessments occurred on July 25th and 26th in 2019 and June 26th in 2020. Fall assessments occurred on September 6th and 7th in 2019. For 2020, assessments occurred at apple harvest for Gala on September 9th, Honeycrisp on September 16th, and Fuji on October 15th. Ten trees were randomly selected in the central three rows of each apple variety, in each experimental plot avoiding the 5 m meters nearest the center where the separation between the above canopy and in canopy SSCDS was located. Twenty-one terminals and apples were sampled per tree with samples evenly distributed across the east and west sides and from the top, middle and lower third of the canopy yielding 210 terminals and fruit per variety per plot. Foliage, counts were made of the number of terminal leaves with clean leaves, incidence of apple scab (*Venturia inaequalis*), leaf hopper (*Typhlocyba pomaria*) feeding, (cedar apple rust (*Gymnosporangium juniperi-virginianae*), powdery mildew (*Podosphaera leucotricha),* insect defoliation (multiple sources), mite bronzing (Tetranychidae), and aphids (Aphididae). Fruit included the number of clean fruit, the number of fruit with apple scab (*Venturia inaequalis)*, powdery mildew (*Podosphaera leucotricha)*, cedar apple rust (*Gymnosporangium juniperi-virginianae Schwein)*, sooty blotch and flyspeck (microbial complex), rotted fruit, tortricid moth sting and entry (Tortricidae), plum curculio sting and feeding (*Conotrachelus nenuphar (Herbst*), and sucking insect damage (Heteroptera). Incidence of bitter pit disorder in Honeycrisp apples was also recorded.

Fruit quality and yield assessment. Apple yield was calculated by apple counts carried out for each tree undergoing damage assessment. Fruit quality was assessed at harvest for each variety in 2020 with the collection of apples of each variety for each treatment at harvest. These apples were chosen randomly, selecting ten per tree, in 10 trees with samples evenly distributed across the east and west sides and from the top, middle and lower third of the canopy yielding one-hundred apples per variety per treatment. Apple weight was measured using a lab scale weighing each individual apple. Size was assessed measuring the diameter of the apple with a digital caliper (Clockwise tools Inc., Valencia, CA, USA). Yield in metric tons per hectare was approximated using mean apple weight and mean apple counts extrapolated using the number of apples per tree and the number of trees per hectare.

Statistical Analysis Software. All statistical analyses were carried out using RStudio (1.4.1717 ver. 3.4.0, R Foundation for Statistical Computing, Vienna, Austria).

Coverage Analysis. Percent coverage data was analyzed using a factorial analysis of variance (ANOVA) and post-hoc analysis using Tukey's HSD (honest significant difference) with a significance level of $\alpha=0.05$. An arcsine transformation was carried out to ensure that data met assumptions of normality and heteroskedasticity. After detection of no significant differences between varieties, a single interactive model was used with treatment, canopy strata, and card face as fixed factors and percent coverage as a response variable.

Deposition Analysis. Deposition was analyzed using a factorial analysis of variance (ANOVA) and post-hoc analysis using Tukey's HSD (honest significant difference) with a significance level of $\alpha=0.05$. A quarter root transformation was carried out to ensure that data met assumptions of normality and heteroskedasticity. Separate models were carried out for each variety with fixed factors of treatment, and canopy strata, flux as a percent of the applied rate was the response variable.

Damage evaluations: Foliar. Damage evaluations were analyzed using Kruskall-Wallace analysis of variance at an alpha level of 0.05 followed by a post-hoc, pairwise Conover-Iman test, in which the null hypothesis was rejected if $p<\alpha/2$, $\alpha=0.05$. Kruskall-Wallis analysis of variance was chosen as the data did not meet normality assumptions required of a one way ANOVA. Separate models were generated for response variables, percentage of clean foliage, percentage of arthropod damage foliage, and percentage of disease damaged foliage. The percentage of arthropod damaged foliage combined counts of damage caused by insect defoliation, mite bronzing, and aphids divided by total number of leaves assessed. Disease damage combined damage caused by apple scab, powdery mildew, and cedar apple rust, divided by the number of leaves assessed. For each of these response variables models were generated separating years assessed (2019, 2020), seasons assessed (summer, fall), and variety (Gala, Honeycrisp, Fuji), with the fixed factor of treatment (above canopy SSCDS, in canopy SSCDS, Airblast).

Damage evaluations: Fruit: Fruit damage analysis was performed in the same manner as foliar damage. Response variables were clean fruit, arthropod damage, and disease. Arthropod damage combined damage caused by tortricid moths, plum curculio, and damage caused by sucking insects. Disease counts combined apple scab, cedar apple rust, sooty blotch and flyspeck, as well as rotted fruit.

Bitter pit Analysis. Analysis of bitter pit disease in Honeycrisp apples was analyzed using Kruskall-Wallace analysis of variance followed by a post-hoc, pairwise Conover-Iman test. The response variable was the percentage of fruit damaged by bitter pit with a fixed factor of treatment.

Fruit Quality Analysis. Analysis of fruit diameter, fruit count, and fruit weight measurements were analyzed using a factorial analysis of variance (ANOVA) and post-hoc analysis using Tukey's HSD (honest significant difference) with a significance level of α=0.05. Separate models were carried out for each variety for each respective response variable of fruit diameter, fruit count per tree, and fruit weight. Treatment was a fixed factor for each.

Harvest Yield Analysis. Harvest yield was the product of mean fruit counts per tree and mean weights of individual apples (grams). Average fruit per tree and average weight per apple were assessed in each treatment within each variety and multiplied giving mean weight in apples per tree. Dividing the length of a hectare (100 m) by row spacing in the orchard (3.35 m) equaled the number of rows per hectare (30 rows/ha). Dividing the width of a hectare (100 m) by tree spacing (.914 m) equals the number of trees per row (109 trees/row). Multiplication of the number of trees per row by the number of rows per hectare equaled the number of trees per hectare (3270 trees/ha). Weight per tree (g) was then multiplied by the number of trees per hectare equaling apple weight in grams per hectare. This value was then converted from g/ha to mt/ha (metric ton/hectare) by multiplying g/ha by 1×10^6.

Harvest yield was analyzed using a factorial analysis of variance (ANOVA) and post-hoc analysis using Tukey's HSD (honest significant difference) with a significance level of α=0.05. Separate models were carried out for each variety with a fixed factor of treatment.

3.3. Results and Discussion

Table 3.3 Weather conditions recorded during coverage and deposition evaluations. Mean temperature, Mean % relative humidity, and wind speed during coverage and deposition evaluations. Winds predominantly out of the NNW during applications.

Treatment	Mean temp. °C	Mean % RH	Wind speed ms^{-1}		
			Min	Max	Mean
Above Canopy SSCDS	26.4	63.5	0.3	1.6	1.2
In Canopy SSCDS	25.9	65.4	0.6	2.0	1.4

Coverage. No significant differences among varieties (Gala, Honeycrisp, Fuji) or treatments (above canopy SSCDS, in canopy SSCDS) ($F_{2,102}$=0.90, p=0.41 and $F_{1,102}$=2.21, p=0.14) were detected for coverage. Significant differences were detected between canopy strata (Top, Middle, Bottom) ($F_{2,102}$=5.03, p=0.008), water sensing paper face (Adaxial, Abaxial) ($F_{1,102}$=100.96, p<0.001), and interaction between treatment and canopy strata ($F_{2,102}$=13.35, p<0.001).

The greatest coverage was in the top of the canopy in the above canopy SSCDS in the adaxial face of the samplers, coverage decreased descending with strata (Table 3.4) (Figure 3.1 A). Abaxial mean coverage for the top and middle stratas of the canopy were nearly equivalent $\bar{x}$= 21.02% ± 7.32%, $\bar{x}$= 21.64% ± 8.78% respectively) with mean abaxial coverage at the bottom of the canopy being the lowest of the three ($\bar{x}$= 3.97% ± 3.41%).

The in canopy SSCDS mean coverage for adaxial surfaces was greatest for the top and bottom strata of the canopy ($\bar{x}$= 38.54% ± 6.76%, $\bar{x}$=45.95% ± 11.47% respectively). Coverage for abaxial surfaces were not significantly different with means at top, middle, and bottom strata with similar values ($\bar{x}$= 9.15% ± 6.10%, $\bar{x}$= 10.11% ± 6.73%, $\bar{x}$= 12.05% ± 6.70% respectively).

Coverage was greatest on the adaxial surfaces for both treatments (above canopy SSCDS, in canopy SSCDS) (Table 3.4). The above canopy and in canopy SSCDS mean coverage values were significantly different at the top of the canopy at both the adaxial and abaxial faces. Coverage from the above canopy SSCDS at the top strata in the adaxial and abaxial positions ($\bar{x}$= 54.10% ± 12.28%, $\bar{x}$= 21.02% ± 7.32% respectively) were significantly greater than those positions treated by the in canopy SSCDS ($\bar{x}$= 38.54% ± 6.76%, $\bar{x}$= 9.15% ± 6.10% respectively). This was likely due to emitter placement and greater flow rate associated with the above canopy SSCDS whose emitters were only present above the canopy. Abaxial surfaces for all strata treated by the in canopy SSCDS did not statistically differ, this was also true for the adaxial surfaces (Table 3.4) (Figure 3.7B). This was not the case for the above canopy SSCDS, whose coverage was significantly different for the top of the canopy in the abaxial face and the middle strata of the abaxial and adaxial faces (Table 3.4). These differences suggest that the in canopy SSCDS provided a more uniform coverage to the canopy.

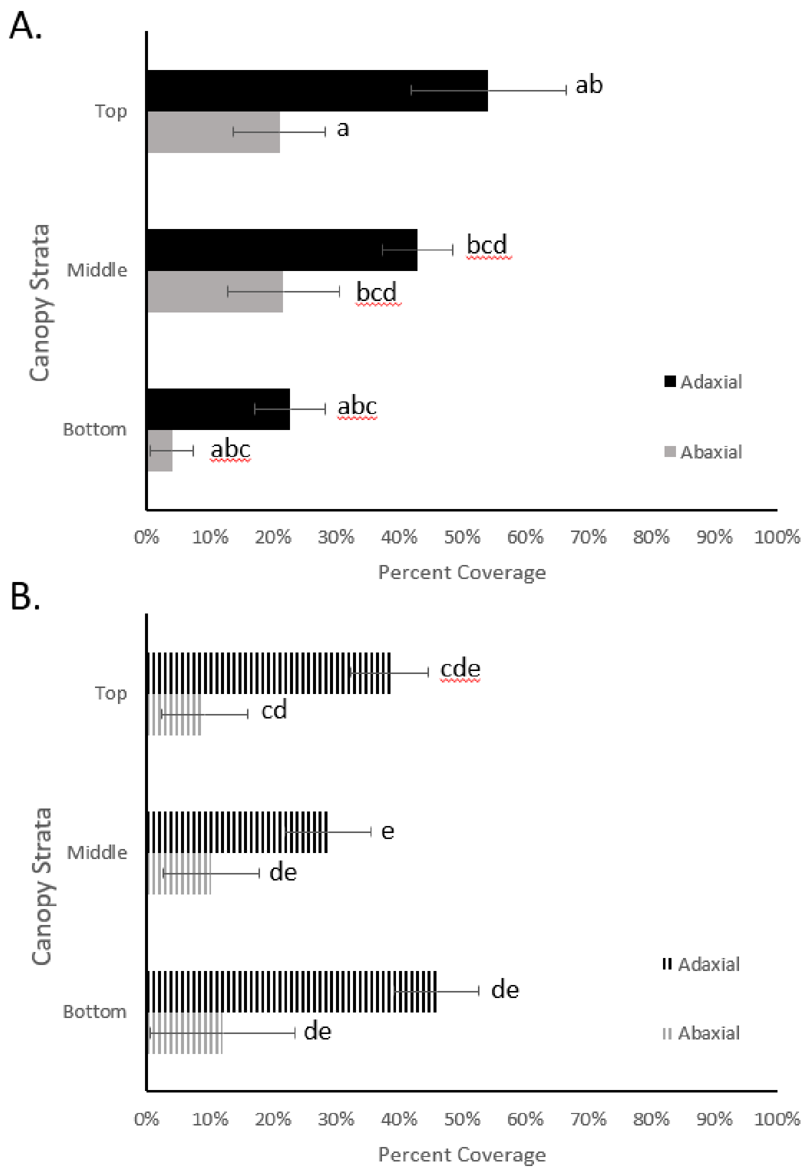

Figure 3.4- A,B – Mean coverage ± SEM in above canopy and in canopy SSCDS. Coverage from treatment by the Above canopy SSCDS (A.) and in canopy SSCDS (B.) by orchard strata (top, middle, bottom of the canopy) and sampler face: Adaxial (upward facing), Abaxial (downward facing). Differing letters denote significant differences between sampler surface and canopy placement at α=0.05.

Table 3.4- Mean ±SEM percent coverage at strata, height and face. Percent coverage provided by treatments at stratus (Top ⅓, Middle ⅓, Bottom ⅓) within the canopy, and face (Adaxial: upward facing, Abaxial: downward facing) of water sensitive paper. Differing letters in Tukey's HSD column signify significant differences between face and strata at α=0.05.

Treatment	Strata	Face	Mean % coverage	±SEM	
Above Canopy	Top	Abaxial	21.02	7.32	a
		Adaxial	54.10	12.28	ab
	Middle	Abaxial	21.64	8.78	bcd
		Adaxial	42.93	5.62	bcd
	Bottom	Abaxial	3.97	3.42	abc
		Adaxial	22.74	5.52	abc
In Canopy	Top	Abaxial	9.15	6.10	cd
		Adaxial	38.54	6.76	cde
	Middle	Abaxial	10.11	6.73	de
		Adaxial	28.71	7.64	e
	Bottom	Abaxial	12.05	6.70	de
		Adaxial	45.95	11.47	de

Deposition. Analysis of deposition data detected significant differences between apple varieties (Gala, Honeycrisp, Fuji), interaction between variety and treatments (above canopy SSCDS, in canopy SSCDS), as well as interactions between treatments and canopy strata (Top ⅓, Middle ⅓, Bottom ⅓) ($F_{2,300}$=4.36, p=0.01, $F_{2,300}$=4.96, p<0.008, $F_{2,300}$=4.00, p=0.02 respectively). **Gala deposition**. No significant differences were detected between treatments, canopy strata, or interaction factor ($F_{1,102}$=0.032, p=0.86, $F_{2,102}$=0.62, p=0.54, $F_{2,102}$=2.76, p=0.07 respectively.) No significant differences were detected between means for treatments or canopy strata. Mean above canopy SSCDS Gala deposition followed a similar pattern to coverage with higher means associated with positions higher in the canopy. The deposition mean for the in canopy SSCDS was greatest in the bottom of the canopy with middle and top means similar in value, differing from the above canopy SSCDS (Table 3.5) (Figure 3.2).

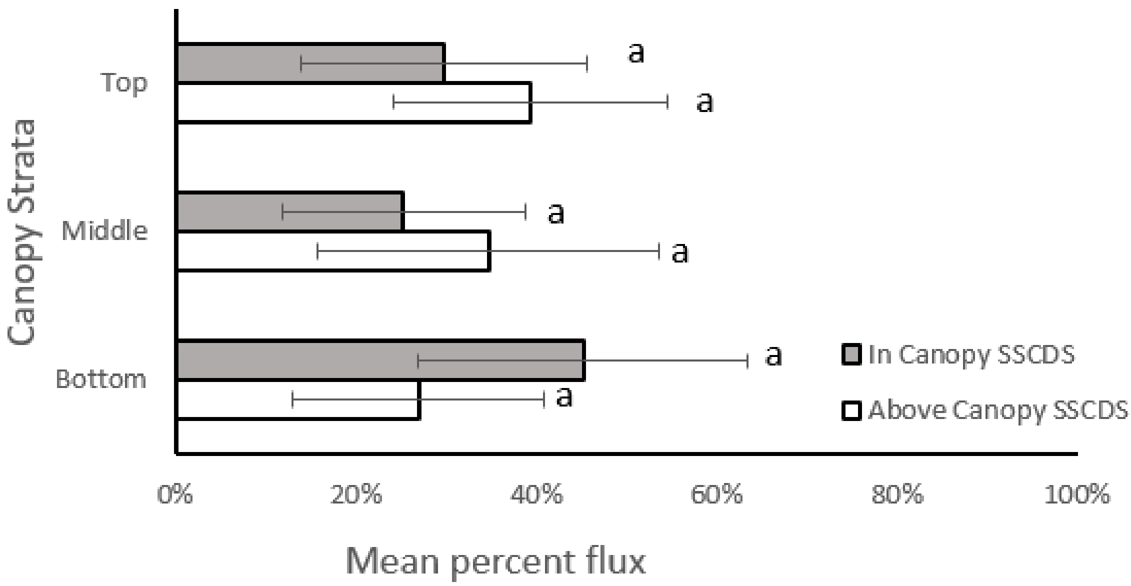

Figure 3.5 - Percent flux as deposition by canopy strata for Gala. Deposition by treatment at strata (Top ⅓, Middle ⅓, Bottom ⅓) within the canopy. Differing letters signify significant differences between treatments in sampler face and strata at α=0.05. No significant differences were detected between treatments in strata for either in canopy or above canopy SSCDS.

Honeycrisp Deposition. No significant differences were detected between canopy strata or treatment's interaction factor between canopy strata ($F_{2,96}$=1.31, p=0.27, $F_{2,96}$=0.69, p=0.51 respectively). A significant difference was detected between the treatments (above canopy SSCDS, in canopy SSCDS) ($F_{1,96}$=6.24, p=0.01). Mean deposition was near equivalent for the in canopy SSCDS across all strata (Bottom, Middle, Top) ($\bar{x}$= 16.56% ± 15.46%, $\bar{x}$= 31.38% ± 18.22%, $\bar{x}$= 20.28% ± 14.95% respectively). Above canopy SSCDS means follow a similar pattern as observed with the Gala variety, a lower mean deposition, lower in the canopy (Figure 3.5).

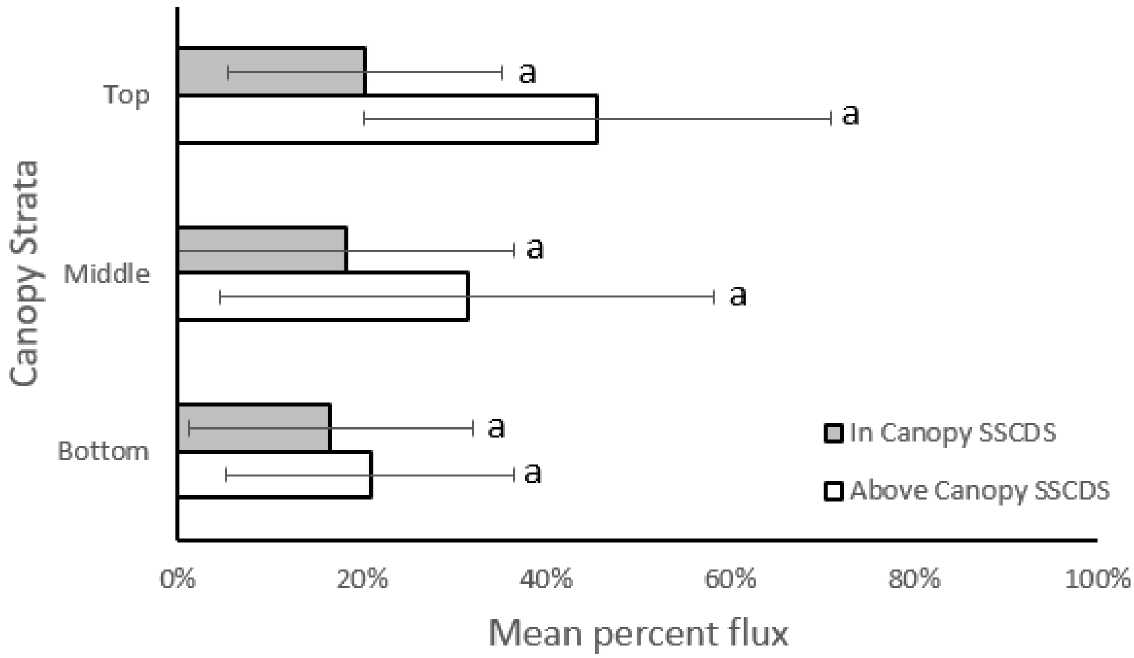

Figure 3.6 - Percent flux as deposition by canopy strata for Honeycrisp. Deposition by treatment at strata (Top ⅓, Middle ⅓, Bottom ⅓) within the canopy. Differing letters signify significant differences between treatments in sampler face and strata at α=0.05. No significant differences were detected between treatments in strata for either the above canopy or in canopy SSCDS.

Fuji Deposition. No significant differences were detected between treatments, canopy strata, or interaction factor ($F_{1,102}$=2.40, p=0.13, $F_{2,102}$=0.36, p=0.70, $F_{2,102}$=1.41, p=0.25 respectively.) Above canopy SSCDS mean deposition was greatest at the top of the canopy and lowest at the bottom, similar to the other varieties. Mean deposition values for the in canopy SSCDS were similar for all strata, similar to the other two varieties (Figure 3.4).

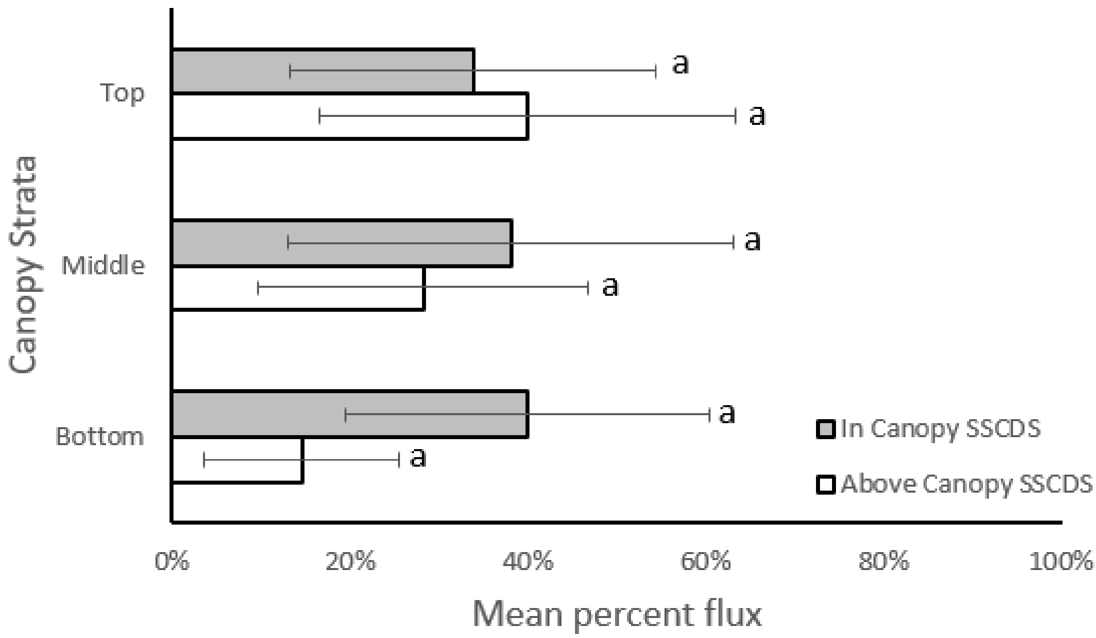

Figure 3.7-Percent flux as deposition by canopy strata for Fuji. Deposition by treatment at strata (Top ⅓, Middle ⅓, Bottom ⅓) within the canopy. Differing letters signify significant differences between treatments in sampler face and strata at α=0.05. No significant differences were detected between treatments in strata for either above canopy or in canopy SSCDS.

Table 3.5 Mean percentage of flux ± SEM as deposition. Flux as a percent of the applied rate by treatment and strata (Top ⅓, Middle ⅓, Bottom ⅓) of the canopy. Differing letters signify significant differences between treatments within strata for each variety at α=0.05.

Variety	Treatment	Strata	%Flux/deposition	±SEM	
Gala	Above Canopy	Bottom	26.89%	13.89%	a
		Middle	34.67%	18.87%	a
		Top	39.28%	15.24%	a
	In Canopy	Bottom	45.22%	18.25%	a
		Middle	25.28%	13.51%	a
		Top	29.78%	15.84%	a
Honeycrisp	Above Canopy	Bottom	20.88%	15.63%	a
		Middle	31.38%	26.91%	a
		Top	45.50%	25.41%	a
	In Canopy	Bottom	16.56%	15.46%	a
		Middle	18.22%	18.31%	a
		Top	20.28%	14.95%	a

Table 3.5 (cont'd)

Fuji	Above Canopy	Bottom	14.61%	10.98%	a
		Middle	28.22%	18.56%	a
		Top	39.94%	23.44%	a
	In Canopy	Bottom	39.94%	20.44%	a
		Middle	38.11%	25.01%	a
		Top	33.83%	20.65%	a

Coverage and Deposition Conclusions. Coverage patterns for above canopy and in canopy SSCDS differed with the highest coverage means located higher in the canopy for the above canopy while means were more evenly distributed for the in canopy SSCDS. The in canopy SSCDS mean coverage means were most similar at the top and the bottom strata in the adaxial faces, with all three abaxial faces being near equivalent. These patterns were most likely due to the distribution of the emitters. The above canopy SSCDS with emitters located only at the top of the canopy had the highest coverage at the top of the canopy. This was clearest when comparing adaxial and abaxial faces at the top strata and the bottom strata with the lowest coverage being the abaxial face of the bottom strata. Similar coverage patterns for an in canopy SSCDS were reported by Owen-Smith (2019) with the SSCDS providing similar coverage to adaxial faces at all strata (Figure 3.1B) (Table 3.4).

Deposition means were significantly different between apple varieties. These differences may be attributed to physiology with differing canopy densities between varieties or in the location of the varieties themselves in the plots. Deposition for the in canopy SSCDS was highest at the top and bottom strata in Gala and Fuji (Table 3.5). Analysis of deposition in Honeycrisp did detect a significant difference between the above canopy and in canopy SSCDS. Honeycrisp deposition measurements for the in canopy SSCDS were similar at each strata and lower than the above canopy at each strata (Figure 3.6) (Table 3.5). Deposition in the above canopy SSCDS decreased with greater distance from the top of the canopy. Fuji deposition was determined to have no significant difference between treatments or strata, its mean deposition was similar to gala but with greater similarity in mean deposition associated with the in canopy SSCDS (Tables 3.4 & 3.5).

Damage Evaluations: 2019 Clean Fruit. The percentage of clean fruit analyzed in the summer of 2019 detected no significant differences between treatments for Gala, Honeycrisp, or Fuji (χ^2=2.66, df= 2, p=0.27, χ^2=1.03, df= 2, p=0.60, and χ^2=1.03, df= 2, p=0.59 respectively). A majority of the fruit assessed was determined to be clean for all varieties and treatments, with all means near one hundred percent (Table 3.6).

Analysis of the percentage of clean fruit in the fall of 2019 detected statistically significant differences between treatments in Gala and Fuji (χ^2=38.09, df= 2, p=<0.001, χ^2=12.49, df= 2, p=<0.001 respectively). In Gala, significant differences were detected between the in canopy SSCDS and the Airblast and the above canopy SSCDS and the Airblast with no significant differences detected between above canopy and in canopy SSCDS (p<0.001,p<0.001, and p=0.50 respectively). In Gala, the percentage of clean fruit was highest for fruit treated by the above canopy and in canopy SSCDS compared to the Airblast ($\bar{x}$= 95.71% ± 4.53%, $\bar{x}$= 95.24 ± 5.67%, $\bar{x}$= 86.83 ± 7.64% respectively). In Fuji, a significant difference was detected between the above canopy SSCDS and Airblast treatments (p<0.001) with no significant differences detected between the above and in canopy SSCDS or the in canopy SSCDS and the Airblast (p=0.05, p=0.03 respectively). In Fuji, the percentage of clean fruit treated by the Airblast was greater than the percentage of clean fruit treated by the above canopy SSCDS ($\bar{x}$= 95.71% ± 4.53%, $\bar{x}$= 95.24 ± 5.67% respectively).

Damage Evaluations: 2019 Clean Foliage Analysis of the percentage of clean foliage assessed in the summer of 2019 detected no significant differences between treatments in Gala, Honeycrisp, or Fuji (χ^2=5.30, df= 2, p=0.07, χ^2=0.392, df= 2, p=0.822, and χ^2=0.88, df= 2, p=0.64 respectively). A majority of the foliage assessed in the summer of 2019 was free of damage, percentages of clean foliage in all varieties and treatments were near ninety percent (Table 3.7).

Analysis of the percentage of clean foliage in the fall of 2019 detected no significant differences between treatments in Gala or Honeycrisp (χ^2=3.85, df= 2, p=0.15, χ^2=2.87, df= 2, p=0.24 respectively) with means all approximately ninety percent clean foliage in all treatments. Significant differences were detected between treatments in Fuji (χ^2=16.29, df= 2, p<0.001) between the above canopy SSCDS and the Airblast as well as the in canopy SSCDS and the Airblast (p<0.001, p<0.001 respectively). No significant differences were detected between the in canopy and above canopy SSCDS (p=0.47). The percentages of clean foliage for both the above canopy SSCDS and in canopy SSCDS were greater than the percentage of clean foliage treated by the Airblast ($\bar{x}$= 92.62% ± 5.95%, $\bar{x}$= 91.62 ± 7.72%, $\bar{x}$= 84.60% ± 9.16% respectively).

Damage Evaluations: 2020 Clean Fruit. Analysis of the clean fruit assessed in the summer of 2020 detected no statistically significant differences between treatments in Gala or Honeycrisp (χ^2=2.66, df= 2, p=0.27, χ^2=0.15, df= 2, p=0.93 respectively). Percentages of clean fruit for all treatments in both Gala and Honeycrisp varieties were approximately 100%. Significant differences between treatments were detected for Fuji (χ^2=12.38, df= 2, p=0.002) between the above canopy SSCDS and the Airblast, and the in canopy SSCDS and the Airblast ($p=0.001$, $p=0.008$ respectively). No significant differences were detected between the in canopy and above canopy SSCDS ($p=0.20$). The percentage of clean fruit treated by the Airblast in Fuji was slightly higher than the percentage of clean fruit treated by both the above canopy and in canopy SSCDS ($\underline{x}$= 99.44% ± 1.50%, $\bar{x}$= 96.67 ± 3.87%, $\bar{x}$= 97.22% ± 3.87% respectively) (Table 3.6).

Analysis of the clean fruit assessed in the fall of 2020 detected no significant differences between treatments for Gala, Honeycrisp, or Fuji varieties ($\chi^2=4.30$, df= 2, $p=0.12$, $\chi^2=1.45$, df= 2, $p=0.48$, $\chi^2=2.73$, df= 2, $p=0.25$ respectively). A majority of the fruit assessed in the fall of 2020 were free of damage with the percentage of clean fruit detected near 100%. (Table 3.6)

Damage Evaluations: 2020 Clean Foliage. The analysis of clean foliage in the summer of 2020 detected no statistically significant differences between treatments in Gala, Honeycrisp, or Fuji ($\chi^2=3.24$, df= 2, $p=0.20$, $\chi^2=0.98$, df= 2, $p=0.61$, $\chi^2=2.36$, df= 2, $p=0.31$ respectively). A majority of the foliage assessed in the summer of 2020 was free of damage, the proportion of clean foliage detected in all varieties and treatments was greater than ninety percent (Table 3.7).

The percentage of clean foliage analyzed for the fall of 2020 detected no significant differences between treatments in Fuji ($\chi^2=1.80$, df= 2, $p=0.41$) with means near eighty percent clean foliage (Table 3.7). Significant differences were detected between treatments for Gala and Honeycrisp ($\chi^2=9.18$, df= 2, $p=0.01$, $\chi^2=6.96$, df= 2, $p=0.03$ respectively). Significant differences were detected between treatments in Honeycrisp using omnibus testing, however post hoc testing did not detect significant differences between treatments ($p>.025$). The mean percent clean foliage for treatments in Honeycrisp ranged from approximately eighty-four to ninety percent. In Gala no significant differences were detected between the above canopy SSCDS and Airblast or in canopy SSCDS and Airblast ($p=0.11$, $p=0.21$ respectively). Significant differences were detected between the above canopy SSCDS and in canopy SSCDS ($p=0.01$) with the percentage of clean foliage higher in trees treated by the above canopy SSCDS ($\bar{x}$= 92.26% ± 5.44%, $\bar{x}$ = 87.65 ± 11.45% respectively). Overall, a majority of the foliage assessed in the fall of 2020 was free of pest damage with some differences between SSCDS configurations detected in Gala.

Table 3.6 Mean ± SEM percentage of clean fruit detected in 2019 and 2020. Clean fruit by variety, treatment, season. Differing letters signify significant differences between treatments within year, variety, and season at α=0.025.

2019					
Variety	Season	Treatment	% Clean Fruit	± SEM	
Gala	Summer	Above Canopy	96.25%	4.38%	a
		In Canopy	95.56%	5.04%	a
		Airblast	93.96%	5.84%	a
	Fall	Above Canopy	95.71%	4.53%	a
		In Canopy	95.24%	5.67%	a
		Airblast	86.83%	7.64%	b
Honeycrisp	Summer	Above Canopy	97.78%	3.01%	a
		In Canopy	96.83%	4.42%	a
		Airblast	96.67%	3.92%	a
	Fall	Above Canopy	95.71%	5.45%	a
		In Canopy	97.14%	3.75%	a
		Airblast	96.83%	4.59%	a
Fuji	Summer	Above Canopy	96.61%	4.41%	a
		In Canopy	95.60%	4.98%	a
		Airblast	96.98%	3.60%	a
	Fall	Above Canopy	83.33%	10.14%	a
		In Canopy	86.03%	10.92%	a
		Airblast	92.38%	6.08%	b
2020					
Gala	Summer	Above Canopy	98.75%	2.43%	a
		In Canopy	98.61%	2.28%	a
		Airblast	99.31%	1.98%	a
	Fall	Above Canopy	93.59%	5.22%	a
		In Canopy	91.42%	5.66%	a
		Airblast	94.48%	4.16%	a

Table 3.6 (cont'd)

Honeycrisp	Summer	Above Canopy	99.44%	1.50%	a
		In Canopy	99.31%	1.98%	a
		Airblast	99.31%	1.66%	a
	Fall	Above Canopy	98.31%	2.50%	a
		In Canopy	98.99%	2.03%	a
		Airblast	98.69%	2.45%	a
Fuji	Summer	Above Canopy	96.67%	3.87%	a
		In Canopy	97.22%	3.87%	a
		Airblast	99.44%	1.50%	b
	Fall	Above Canopy	87.73%	7.95%	a
		In Canopy	91.39%	5.99%	a
		Airblast	91.67%	5.19%	a

Table 3.7 Mean ± SEM percentage of clean foliage detected in 2019 and 2020. Percentage of clean foliage detected by variety, treatment, season. Differing letters signify significant differences between treatments within year, variety, and season at α=0.025.

2019					
Variety	Season	Treatment	% Clean Foliage	± SEM	
Gala	Summer	Above Canopy	87.61%	8.84%	a
		In Canopy	89.32%	7.05%	a
		Airblast	91.84%	7.92%	a
	Fall	Above Canopy	86.38%	10.07%	a
		In Canopy	87.34%	7.90%	a
		Airblast	83.51%	8.96%	b
Honeycrisp	Summer	Above Canopy	89.13%	8.21%	a
		In Canopy	89.26%	6.97%	a
		Airblast	90.28%	6.83%	a
	Fall	Above Canopy	84.73%	10.38%	a
		In Canopy	83.98%	11.34%	a
		Airblast	81.64%	9.82%	a
Fuji	Summer	Above Canopy	91.38%	7.22%	a
		In Canopy	93.24%	5.41%	a
		Airblast	91.14%	6.76%	a
	Fall	Above Canopy	92.62%	5.95%	a
		In Canopy	91.62%	7.72%	a
		Airblast	84.60%	9.16%	b

Table 3.7 (cont'd)

2020					
Gala	Summer	Above Canopy	94.75%	5.79%	a
		In Canopy	93.35%	5.53%	a
		Airblast	95.00%	5.39%	a
	Fall	Above Canopy	92.26%	5.44%	a
		In Canopy	87.65%	6.61%	a
		Airblast	89.78%	5.75%	a
Honeycrisp	Summer	Above Canopy	96.25%	5.13%	a
		In Canopy	96.00%	4.60%	a
		Airblast	96.92%	4.77%	a
	Fall	Above Canopy	86.87%	7.01%	a
		In Canopy	89.31%	6.80%	a
		Airblast	84.17%	8.15%	a
Fuji	Summer	Above Canopy	95.28%	5.36%	a
		In Canopy	96.94%	4.09%	a
		Airblast	95.28%	4.79%	b
	Fall	Above Canopy	75.14%	13.52%	a
		In Canopy	76.96%	12.56%	a
		Airblast	82.31%	7.15%	a

Damage Evaluations: 2019 Arthropod Damaged Fruit. Analysis of arthropod damaged fruit assessed in the summer 2019 detected no significant differences between treatments in Honeycrisp or Fuji (χ^2=2.45, df= 2, p=0.29, χ^2=2.03, df= 2, p=0.60 respectively). The percentage of damaged fruit detected in both varieties for all treatments was under 1%. Significant differences were detected between treatments in Gala (χ^2=14.22, df= 2, p<0.001) between the above canopy SSCDS and the in canopy SSCDS as well as between the above canopy SSCDS and the Airblast (p<0.001, p=0.001 respectively). No significant differences were detected between the in canopy SSCDS and the Airblast (p=0.49). The percentage of damaged apples treated by the above canopy SSCDS was greater than the percentage of damaged apples treated by either the in canopy SSCDS or Airblast ($\bar{x}$= 2.02% ± 3.58%, $\bar{x}$= 0.16 ± 0.87%, $\bar{x}$=0.14% ± 0.76% respectively) (Table 3.8).

Analysis of arthropod damaged fruit from the fall of 2019 detected no statistically significant differences between treatments for Gala or Fuji (χ^2=4.01, df= 2, p=0.13, χ^2=1.00, df= 2, p=0.61 respectively). Omnibus testing detected significant differences between treatments for Honeycrisp (χ^2=6.45, df= 2, p=0.04), however, post-hoc analysis detected no significant differences between treatments ($p>.025$). A majority of the fruit assessed were free of pest damage with means near or below one percent damaged fruit (Table 3.8).

Damage Evaluations: Arthropod Damaged Foliage. Analysis of foliar arthropod damage from the summer 2019 detected no statistical differences between treatments for Honeycrisp or Fuji varieties (χ^2=0.39, df= 2, p=0.82, χ^2=0.88, df= 2, p=0.64 respectively) with the percentages of damaged foliage ranging from ~ 3% - 6% (Table 3.9).

Significant differences between treatments were detected in Gala (χ^2=13.88, df= 2, p<0.001) between the above canopy SSCDS and Airblast as well as the in canopy SSCDS and Airblast. No statistical differences were detected between above canopy SSCDS and in canopy SSCDS (p<0.001, p=0.001, p=0.11 respectively). The percentage of foliar damage was higher in trees treated by both the above canopy and in canopy SSCDS than those treated by the Airblast ($\overline{x}$ = 5.62% ± 6.13%, $\overline{x}$ = 3.88 ± 4.69%, $\overline{x}$= 1.43% ± 3.31% respectively).

Analysis of foliar arthropod damage assessed in the fall of 2019 detected no statistically significant differences between treatments for Gala (χ^2=2.65, df= 2, p=0.27) with the percentages of damaged foliage ranging from ~3% - 4%. Statistically significant differences were detected between treatments for Honeycrisp and Fuji (χ^2=8.19, df= 2, p=0.02, χ^2=23.10, df= 2, p<0.001 respectively). In Honeycrisp significant differences were detected between the above canopy SSCDS and Airblast (p=0.02) and no significant differences were detected between the above canopy and in canopy SSCDS or the in canopy SSCDS and Airblast (p=0.07, p=0.42 respectively). The percentage of arthropod damaged foliage in Honeycrisp was greater in foliage treated by the Airblast when compared to the above canopy SSCDS ($\underline{\chi}$= 14.40% ± 9.36%, $\overline{x}$= 7.91 ± 7.24% respectively). Analysis of foliar damage in Fuji detected significant differences between above canopy SSCDS and Airblast as well as in canopy SSCDS and Airblast (p<0.001, p<0.001 respectively) with no significant differences detected between above and in canopy SSCDS treatments (t=–0.74, p=0.23). Foliage treated by both the above canopy and in canopy SSCDS had less arthropod damage than foliage treated by the Airblast ($\overline{x}$= 2.20% ± 3.47%, $\overline{x}$= 3.30 ± 4.78%, $\overline{x}$ = 8.38% ± 6.90% respectively).

Damage Evaluations: 2020 Arthropod Damaged Fruit. Analysis of the percentage of fruit damaged by arthropods in the summer of 2020 detected no significant differences between treatments in Honeycrisp (χ^2=0, df= 2, p=0.91) with means below 1% for all treatments. No statistical analysis was performed for Gala or Fuji as no damage was detected for Gala in any treatment and no damage was present for the above canopy SSCDS or Airblast treatments for Fuji.

Analysis of the percentage of fruit damaged by arthropods in the fall of 2020 detected no significant differences between treatments in Honeycrisp (χ^2=2.02, df= 2, p=0.36) with percentages of damaged fruit well below 1% (Table 3.8). For Gala and Fuji no statistical analysis was performed due to no arthropod damage detected in any treatment for Gala and no damage detected in either SSCDS system in Fuji.

Damage Evaluations: 2020 Arthropod Damaged Foliage. Analysis of arthropod damaged foliage for summer of 2020 detected no significant differences between treatments for Gala, Honeycrisp, or Fuji (χ^2=3.24, df= 2, p=0.20, χ^2=0.76, df= 2, p=0.68, χ^2=0.97, df= 2, p=0.61 respectively) with means ranging from 1.39%-3.46% damaged foliage.

Analysis of arthropod damaged foliage from the fall of 2020 detected no significant differences between treatments in Fuji (χ^2=4.27, df= 2, p=0.12) with means ranging from 2.48%-4.29% damaged foliage. Significant differences were detected between treatments in Gala and Honeycrisp (χ^2=7.31, df= 2, p=0.03, χ^2=7.43, df= 2, p=0.02 respectively). Post-hoc analysis of Gala detected no significant differences between treatments, means ranged from 0.14%-1.23% damaged foliage. Analysis of Honeycrisp detected significant differences between the in canopy SSCDS and Airblast (p=0.021) with a greater percentage of damaged foliage treated by the Airblast compared to the in canopy SSCDS ($\overline{x}$ = 15.83 ± 8.15%, $\overline{x}$ = 10.56% ± 6.75%).

Table 3.8 Mean ± SEM percentage of arthropod damaged fruit detected in 2019 and 2020. Percentages of arthropod damaged fruit detected by variety, treatment, season. Differing letters signify significant differences between treatments within year, variety, and season at α=0.025.

2019					
Variety	Season	Treatment	% Arth. Damage	±SEM	
Gala	Summer	Above Canopy	2.02%	3.58%	a
		In Canopy	0.16%	0.87%	a
		Airblast	0.14%	0.76%	b
	Fall	Above Canopy	0.32%	1.22%	a
		In Canopy	0.00%	0.00%	a
		Airblast	0.00%	0.00%	a
Honeycrisp	Summer	Above Canopy	0.95%	2.07%	a
		In Canopy	0.32%	1.22%	a
		Airblast	0.48%	1.49%	a
	Fall	Above Canopy	1.27%	2.66%	a
		In Canopy	0.16%	0.87%	b
		Airblast	0.32%	1.22%	b

Table 3.8 (cont'd)

Fuji	Summer	Above Canopy	0.53%	2.20%	a
		In Canopy	0.14%	0.76%	a
		Airblast	0.00%	0.00%	a
	Fall	Above Canopy	0.16%	0.87%	a
		In Canopy	0.00%	0.00%	a
		Airblast	0.16%	0.87%	a
2020					
Gala	Summer	Above Canopy	0.00%	0.00%	a
		In Canopy	0.00%	0.00%	a
		Airblast	0.00%	0.00%	a
	Fall	Above Canopy	0.00%	0.00%	a
		In Canopy	0.00%	0.00%	a
		Airblast	0.00%	0.00%	a
Honeycrisp	Summer	Above Canopy	0.14%	0.76%	a
		In Canopy	0.14%	0.76%	a
		Airblast	0.14%	0.76%	a
	Fall	Above Canopy	0.14%	0.76%	a
		In Canopy	0.30%	1.15%	a
		Airblast	0.00%	0.00%	a
Fuji	Summer	Above Canopy	0.00%	0.00%	
		In Canopy	0.14%	0.76%	
		Airblast	0.00%	0.00%	
	Fall	Above Canopy	0.00%	0.00%	a
		In Canopy	0.00%	0.00%	a
		Airblast	0.28%	1.07%	a

Table 3.9 Mean ± SEM percentage of arthropod damaged foliage detected in 2019 and 2020. Arthropod damaged foliage detected by variety, treatment, and season. Differing letters signify significant differences between treatments within year, variety, and season at α=0.025.

2019					
Variety	Season	Treatment	% Arth. Damage	±SEM	CLD
Gala	Summer	Above Canopy	5.62%	6.13%	a
		In Canopy	3.88%	4.69%	a
		Airblast	1.43%	3.31%	b
	Fall	Above Canopy	2.85%	6.58%	a
		In Canopy	3.93%	5.38%	a
		Airblast	4.10%	4.99%	a

Table 3.9 (cont'd)

Honeycrisp	Summer	Above Canopy	5.30%	4.81%	a
		In Canopy	5.81%	5.37%	a
		Airblast	3.93%	4.46%	a
	Fall	Above Canopy	7.91%	7.24%	a
		In Canopy	12.87%	9.86%	ab
		Airblast	14.40%	9.36%	b
Fuji	Summer	Above Canopy	3.54%	4.19%	a
		In Canopy	2.50%	3.36%	a
		Airblast	2.98%	3.78%	a
	Fall	Above Canopy	2.20%	3.47%	a
		In Canopy	3.30%	4.78%	a
		Airblast	8.38%	6.90%	b
2020					
Gala	Summer	Above Canopy	2.76%	3.86%	a
		In Canopy	3.46%	4.45%	a
		Airblast	1.39%	2.75%	a
	Fall	Above Canopy	0.56%	1.50%	ab
		In Canopy	0.14%	0.76%	a
		Airblast	1.23%	2.15%	b
Honeycrisp	Summer	Above Canopy	1.94%	3.23%	a
		In Canopy	2.27%	3.23%	a
		Airblast	1.94%	3.89%	a
	Fall	Above Canopy	13.13%	7.01%	ab
		In Canopy	10.56%	6.75%	a
		Airblast	15.83%	8.15%	b
Fuji	Summer	Above Canopy	2.78%	4.69%	a
		In Canopy	1.67%	3.46%	a
		Airblast	1.81%	2.97%	a
	Fall	Above Canopy	2.48%	3.27%	a
		In Canopy	2.97%	3.53%	a
		Airblast	4.29%	4.06%	a

Damage Evaluations: 2019 Disease Damaged Fruit. Analysis of disease damaged fruit from the summer of 2019 detected no significant differences between treatments for Honeycrisp or Fuji varieties. (χ^2=3.83, df= 2, p=0.60, χ^2=1.64, df= 2, p=0.44 respectively) The percentages of damaged fruit ranged from approximately 1%-3% in Honeycrisp and 3%-4% in Fuji. Significant differences between treatments were detected for Gala (χ^2=9.78, df= 2, p<0.001) between above canopy and Airblast treatments (t=–3.14, p=0.003). No significant differences were detected between above and in canopy SSCDS or between in canopy SSCDS and Airblast treatments (p=0.04, p=0.11 respectively). In Gala a greater percentage of disease damaged apples were detected when treated by Airblast compared to the in canopy SSCDS ($\bar{x}$= 5.90 ± 5.84%, $\bar{x}$=4.29% ± 5.01% respectively).

Analysis of disease damaged fruit from the fall of 2019 detected no significant differences between treatments for Honeycrisp (χ^2=0.11, df= 2, p=0.95) with means near 3% damaged fruit. Significant differences between treatments were detected for Gala and Fuji (χ^2=40.24, df= 2, p<0.001, χ^2=12.60, df= 2, p=0.002, respectively). In Gala, significant differences were detected between treatments above canopy SSCDS and Airblast and also between in canopy SSCDS and Airblast (p<0.001, p<0.001 respectively). No significant differences were detected between above canopy and in canopy SSCDS (p=0.39). Gala trees treated by Airblast were found to have greater percentages of damaged fruit compared to those treated by either the above canopy or in canopy SSCDS ($\bar{x}$= 13.17 ± 7.64%, $\bar{x}$=3.97% ± 4.46%, $\bar{x}$ =4.76% ± 5.67% respectively). In Fuji, a significant difference was detected between treatments above canopy SSCDS and Airblast (p<0.001). No significant differences were detected between above and in canopy SSCDS or in canopy SSCDS and Airblast (t=1.65, p=0.05 and t=–1.97, p=0.04 respectively). Fuji trees treated by the above canopy SSCDS were found to have a greater percentage of damaged fruit than those treated by the Airblast ($\bar{x}$ = 16.51 ± 10.11%, $\bar{x}$ =7.62% ± 6.08% respectively).

Damage Evaluations: 2019 Disease Damaged Foliage. Analysis of the percentage of disease damaged foliage from the summer of 2019 detected no significant differences between any treatments for Gala, Honeycrisp, or Fuji (χ^2=0.40, df= 2, p=0.82, χ^2=0.31, df= 2, p=0.86, χ^2=2.18, df= 2, p=0.34 respectively). The percentage of damaged foliage in all varieties and treatments ranged from ~ 7%-10%.

Analysis of the percentage of disease damaged foliage from the fall of 2019 detected no significant differences between any treatments for Gala, Honeycrisp, or Fuji (χ^2=4.62, df= 2, p=0.99, χ^2=3.27, df= 2, p=0.19, χ^2=1.10, df= 2, p=0.59 respectively). Means ranged from ~ 6%-19% damaged foliage.

Damage Evaluations: 2020 Disease Damaged Fruit . Analysis of the percentage of disease damage fruit from the summer of 2020 detected no significant differences between treatments for Gala or Honeycrisp (χ^2=2.66, df= 2, p=0.27, χ^2=0.20, df= 2, p=0.91 respectively) with means near 1% damaged fruit across all treatments. Significant differences were detected between treatments for Fuji (χ^2=12.21, df= 2, p=0.002) between the above canopy and Airblast treatments as well as the in canopy and Airblast treatments (p<0.001 and p=0.01 respectively). No significant differences were detected between the in canopy and above canopy SSCDS treatments ($p=0.14$). The percentage of disease damaged fruit in Fuji was greater in trees treated by the above and in canopy SSCDS when compared to the Airblast ($\underline{x}$= 3.33 ± 3.87%, $\underline{x}$=2.64% ± 3.82%, $\underline{x}$=0.56% ± 1.50% respectively).

Analysis of the percentage of disease damaged fruit from the fall of 2020 detected no significant differences between treatments for Gala, Honeycrisp, or Fuji ($\chi^2=4.30$, df= 2, $p=0.12$, $\chi^2=2.33$, df= 2, $p=0.31$, $\chi^2=3.12$, df= 2, $p=0.21$ respectively). The mean percentage of damaged fruit ranged from ~6%-9% for Gala, ~1%-2% for Honeycrisp, and ~9%-13% for Fuji (Table 3.10).

Damage Evaluations: 2020 Disease Damaged Foliage. Analysis of the percentage of disease damaged foliage from the summer of 2020 detected no significant differences between treatments in Gala, Honeycrisp, or Fuji varieties ($\chi^2=1.56$, df= 2, $p=0.46$, $\chi^2=0.88$, df= 2, $p=0.65$, $\chi^2=2.49$, df= 2, $p=0.29$ respectively). The mean percentage of damaged fruit ranged from ~2%-4% for Gala, ~ 1%-2% for Honeycrisp, and ~1%-3% for Fuji (Table 3.11).

Analysis of the percentage of disease damaged foliage from the fall of 2020 detected no significant differences between the treatments in Fuji ($\chi^2=3.39$, df= 2, $p=0.18$), means ranged from ~13%-22%. No statistical analysis was performed on Honeycrisp due to no damage detected in foliage treated by the above canopy SSCDS and Airblast treatments. Mean damage for foliage treated by the in canopy SSCDS was less than 1%. Significant differences in Gala were detected ($\chi^2=10.65$, df= 2, $p=0.005$) between the treatments above canopy and in canopy SSCDS ($p=0.002$). No significant differences were detected between the above canopy SSCDS and Airblast or in canopy SSCDS and Airblast ($p=0.15$, $p=0.09$ respectively). The percentage of damaged foliage in Gala treated by the in canopy SSCDS was greater than foliage treated by the above canopy SSCDS ($\overline{x}$ = 12.21 ± 6.65%, $\overline{x}$ =7.18% ± 5.26% respectively).

Table 3.10- Mean ± SEM percentage of disease fruit detected from 2019 and 2020. Percentage of disease damaged fruit detected by variety, treatment, and season. Differing letters signify significant differences between treatments within year, variety, and season at α=0.025.

2019					
Variety	Season	Treatment	% Dis. Damage	±SEM	
Gala	Summer	Above Canopy	1.73%	2.69%	a
		In Canopy	4.29%	5.01%	ab
		Airblast	5.90%	5.84%	b
	Fall	Above Canopy	3.97%	4.46%	a
		In Canopy	4.76%	5.67%	bc
		Airblast	13.17%	7.64%	c
Honeycrisp	Summer	Above Canopy	1.27%	2.36%	a
		In Canopy	2.86%	4.32%	a
		Airblast	2.86%	3.54%	a
	Fall	Above Canopy	3.02%	5.02%	a
		In Canopy	2.70%	3.69%	a
		Airblast	2.86%	4.49%	a
Fuji	Summer	Above Canopy	2.86%	3.95%	a
		In Canopy	4.27%	4.85%	a
		Airblast	3.02%	3.60%	a
	Fall	Above Canopy	16.51%	10.11%	a
		In Canopy	13.81%	10.88%	a
		Airblast	7.62%	6.08%	b
2020					
Gala	Summer	Above Canopy	1.25%	2.43%	a
		In Canopy	1.39%	2.28%	a
		Airblast	0.69%	1.98%	a
	Fall	Above Canopy	6.41%	5.22%	a
		In Canopy	8.58%	5.66%	a
		Airblast	5.52%	4.16%	a
Honeycrisp	Summer	Above Canopy	0.42%	1.30%	a
		In Canopy	0.56%	1.85%	a
		Airblast	0.56%	1.50%	a
	Fall	Above Canopy	1.55%	2.41%	a
		In Canopy	0.71%	1.71%	a
		Airblast	1.31%	2.45%	a
Fuji	Summer	Above Canopy	3.33%	3.87%	a
		In Canopy	2.64%	3.82%	a
		Airblast	0.56%	1.50%	a
	Fall	Above Canopy	12.27%	7.95%	a
		In Canopy	8.61%	5.99%	a
		Airblast	8.06%	5.22%	a

Table 3.11- Mean ± SEM percentages of disease damaged foliage from 2019 and 2020. Disease damaged foliage detected by variety, treatment, and season. Differing letters signify significant differences between treatments within year, variety, and season at α=0.025.

Variety	Season	Treatment	% Dis. Damage	±SEM	
2019					
Gala	Summer	Above Canopy	10.11%	9.62%	a
		In Canopy	9.18%	8.54%	a
		Airblast	13.33%	30.85%	a
	Fall	Above Canopy	16.50%	14.62%	a
		In Canopy	12.17%	10.20%	a
		Airblast	18.84%	14.35%	a
Honeycrisp	Summer	Above Canopy	8.74%	11.28%	a
		In Canopy	6.58%	6.75%	a
		Airblast	7.90%	8.02%	a
	Fall	Above Canopy	15.97%	32.45%	a
		In Canopy	6.32%	12.05%	a
		Airblast	6.76%	13.18%	a
Fuji	Summer	Above Canopy	7.23%	8.77%	a
		In Canopy	5.60%	6.96%	a
		Airblast	7.90%	7.45%	a
	Fall	Above Canopy	6.99%	7.99%	a
		In Canopy	7.42%	8.97%	a
		Airblast	10.86%	11.56%	a
2020					
Gala	Summer	Above Canopy	2.48%	3.61%	a
		In Canopy	3.19%	3.35%	a
		Airblast	3.61%	4.87%	a
	Fall	Above Canopy	7.18%	5.26%	a
		In Canopy	12.21%	6.65%	b
		Airblast	8.99%	5.29%	a
Honeycrisp	Summer	Above Canopy	1.81%	2.77%	a
		In Canopy	1.73%	3.00%	a
		Airblast	1.13%	2.10%	a
	Fall	Above Canopy	0.00%	0.00%	
		In Canopy	0.14%	0.76%	
		Airblast	0.00%	0.00%	

Table 3.11 (cont'd)

Fuji	Summer	Above Canopy	1.94%	2.84%	a
		In Canopy	1.39%	2.52%	a
		Airblast	2.92%	3.91%	a
	Fall	Above Canopy	22.37%	13.89%	a
		In Canopy	20.07%	12.60%	a
		Airblast	13.40%	6.84%	a

Damage Evaluations: Bitter Pit Disorder in Honeycrisp Apples. Analysis of bitter pit diseased Honeycrisp apples in the Fall of 2020 detected significant differences between the treatments (χ^2=65.39, df= 2, p<0.001) above canopy SSCDS and the Airblast as well as the in canopy SSCDS and the Airblast (p<0.001, p<0.001 respectively.) No significant differences were detected between the above canopy and in canopy SSCDS treatments (p =0.3). Bitter pit incidence was greatest for apples treated with the Airblast sprayer.

Table 3.12 Percentage of bitter pit diseased Honeycrisp apples. Percentage of Honeycrisp apples with bitter pit detected in each treatment. Differing letter denotes significant difference at α=0.025. A significantly greater amount of bitter pit was detected in apples treated by the Airblast.

Treatment	% Bitter pit	±SEM	
Above Canopy	6.93%	12.31%	a
In Canopy	6.94%	8.91%	a
Airblast	27.29%	19.06%	b

Pest Management and Disease Conclusions: Clean fruit. A majority of the fruit assessed in both the summer and fall of 2019 and 2020 were free of damage. Treatments in all varieties for the summer of 2019 and the fall of 2020 did not statistically differ, with means near 100% clean fruit. Analysis of the clean fruit data from the fall of 2019 detected significant differences in treatments for both Gala and Fuji. In Gala, the percentage of clean apples was greater in trees treated by the SSCDS configurations when compared to the Airblast. In Fuji, the opposite: trees treated by the Airblast had a higher percentage of clean fruit. In the summer of 2020, significant differences were detected in Fuji, with the Airblast treated trees having a higher percentage of clean fruit and means across all treatments were near 100% clean fruit. While differences were detected a majority of the fruit assessed in all treatments was free of damage (Table 3.6).

As with fruit, a majority of the foliage assessed in both summer and fall of 2019 and 2020 were free of damage in all treatments. Analysis of clean foliage from the summers of both

2019 and 2020 detected no significant differences between treatments in any varieties with the percentages of clean foliage near ninety percent in 2019 and near 100% in 2020. Significant differences between treatments were detected in the fall of both 2019 and 2020. Airblast treated Fuji foliage from 2019 had lower percentages of clean foliage compared to the SSCDS configurations with Airblast means ~ 6% lower. Gala trees treated by the above canopy SSCDS in the fall of 2020 had ~5% greater clean foliage compared to the in canopy SSCDS (Table 3.7).

Comparing summer and fall for two years, no findings suggest a specific treatment or treatment in variety that provides superior pest management over another. Overall findings suggested adequate pest management from both SSCDS configurations, similar to the Airblast. Owen-Smith et al. (2019) and Owen-Smith (2017) described similar findings with low incidences of apple scab and arthropod damage in apple plots treated by Airblast and in canopy SSCDS.

Pest Management and Disease Conclusions: Arthropod damage. Very little arthropod damaged fruit was detected in summer or fall for both 2019 and 2020. The percentage of damaged fruit assessed in the summer of 2019 was under one percent in all but Gala. In Gala, significant differences were detected between the above canopy SSCDS and both the Airblast and in canopy SSCDS. Trees treated by the above canopy SSCDS had a greater percentage of arthropod damaged fruit than either the Airblast or in canopy SSCDS. For the summer of 2020, little to no damage was detected for any treatments in all three varieties. Little to no damage was detected in the fall of 2019 with all damage <1% aside from the above canopy treatment in Honeycrisp near 1%. Fall of 2020 was similar, with no damage detected in Gala for any treatments, and all other treatments in Honeycrisp and Fuji had less than 1% damage detected. A greater amount of damage was detected in trees treated by the above canopy SSCDS in both summer and fall of 2019 in Gala and Honeycrisp. However, these differences were quite small and the majority of the fruit assessed in the two years of the study were clean for all treatments in all three varieties (Table 3.8).

As with fruit, arthropod damaged foliage assessed in the summer was low, most percentages were < 6%. Analysis of damaged foliage in the summer of 2019 detected no significant differences between treatments in Honeycrisp and Fuji with damages ranging from ~ 3%-6%. Significant differences were detected between treatments in Gala with trees treated by the Airblast having a lower percentage of damaged foliage when compared to either the above canopy or in canopy SSCDS. Analysis of damaged foliage from the summer of 2020 detected no significant differences between treatments in any variety with damages ranging from ~1%-3%. Analysis of foliar damage from the fall of 2019 detected no significant differences between treatments in Gala with damages ranging from ~3%-4%. In Honeycrisp the percentage of damaged foliage was greater in trees treated by the Airblast compared to the above canopy SSCDS. Fuji trees treated by the Airblast had a greater amount of foliar damage than those treated by either SSCDS configuration. Analysis of foliage from the fall of 2020 detected no significant differences between treatments in Gala or Fuji with damage ~1% for Gala and ~2%-4% for Fuji (Table 3.9).

Analysis of arthropod damaged fruit for the summer and fall of both years detected little to no damage. The only significant difference between treatments was detected in the summer of 2019, in Gala, otherwise all other treatments in respective years and varieties were similar (Table 3.8). Similarly, a majority of the foliage assessed for arthropod damage was also clean. Analysis of foliar damage from 2019 detected at least one significant difference between treatments in each variety. These differences do show a pattern of greater foliar damage in trees treated by the Airblast when compared to the above canopy SSCDS. However, foliar damage assessed in the fall of 2020 detected no significant differences between treatments from summer and a significant difference between the SSCDS configurations in Honeycrisp for the fall (Table 3.9). These findings, like the findings from the analysis of clean fruit, suggest that no single treatment provides overall better protection from damage in either fruit or foliage.

Pest Management and Disease Conclusions: Disease Damage. The percentage of disease damaged fruit from the summer of 2019 and 2020 ranged from <1% to ~6% across all treatments in all varieties. Analysis of disease damaged fruit in Gala from the summer of 2019, significant differences were detected between the above canopy SSCDS and Airblast, with less damaged fruit in trees treated by the above canopy SSCDS. No significant differences were detected between treatments in Honeycrisp or Fuji. Analysis of disease damaged fruit in the summer of 2020 detected significant differences between treatments in Fuji with less disease damaged fruit in trees treated by the Airblast when compared to either SSCDS configuration. Analysis of damages from the fall of 2019 detected significant differences between treatments in Gala and Fuji. In Gala, trees treated by the Airblast had a greater percentage of damaged fruit when compared to either SSCDS configuration. In Fuji, trees treated by the above canopy SSCDS had a greater percentage of damaged fruit compared to the Airblast. Analysis of damages from the fall of 2020 detected no significant differences between treatments in any variety (Table 3.10).

Analysis of diseased foliage for the summer and fall of 2019, as well as the summer of 2020 detected no significant differences between treatments in any variety. Analysis of disease damage from the fall of 2020 detected no significant differences between treatments in Honeycrisp or Fuji. In Gala, significant differences were detected between the above and in canopy SSCDS. Trees treated by the in canopy SSCDS had a greater percentage of diseased foliage when compared to the above canopy SSCDS (Table 3.11).

A majority of the fruit and foliage assessed from 2019 and 2020 were free of disease. Analysis of fruit damage detected significant differences between treatments in both Gala and Fuji in both 2019 and 2020 (Table 3.10). Analysis of foliar damage had similar results with the only significant difference occurring in Gala in the fall of 2020 between the SSCDS configurations, otherwise all other treatments in all varieties were similar (Table 3.11). Comparing treatments from significantly different pairs in each variety, no treatment appeared to provide overall better disease management.

Pest Management and Disease Conclusions: Bitter Pit Disorder in Honeycrisp. Analysis of bitter pit incidence in Honeycrisp apples detected significant differences between treatments with the Airblast significantly higher than the SSCDS configurations (Table 3.12). Chances of bitter pit disorder increase with conditions of excessive tree vigor and fruit size (Rosenberger et al. 2004). The percentage of bitter pit affected apples for above canopy and in canopy SSCDS were similar, with values that are approximately four times lower than the Airblast treated apples (Table 3.12). This disorder being correlated with the Airblast treatment was most likely due to a lower than effective concentration of apple thinning agents applied by the SSCDS configurations.

Fruit Quality: Gala Apple Diameter: Analysis of Gala apple diameter detected significant differences ($F_{2,943}$=33.35, $p<0.001$) between above canopy SSCDS and in canopy SSCDS, above canopy SSCDS and Airblast, as well as in canopy SSCDS and Airblast ($p=0.01$, $p<0.001$, $p<0.001$ respectively). Fruit from Above canopy and Airblast treated trees were significantly larger than apples from trees treated by the in canopy SSCDS ($\overline{x}$ = 66.10 mm ± 3.21 mm, $\overline{x}$ = 68.40 mm ± 3.40 mm, $\overline{x}$= 64.77 mm ± 3.20 mm respectively) (Table 3.13) (Figure 3.5)

Fruit Quality: Honeycrisp Apple Diameter: Analysis of Honeycrisp apple diameter detected significant differences ($F_{2,940}$=172.1, $p<0.001$) between above canopy SSCDS and Airblast as well as in canopy SSCDS and Airblast ($p<0.001$, $p<0.001$). No significant differences were detected between in canopy SSCDS and above canopy SSCDS ($p=0.42$). Trees treated by the Airblast had significantly larger apples compared to both the above canopy and in canopy SSCDS ($\overline{x}$ = 83.0 mm ± 3.46 mm, $\overline{x}$ = 73.61 mm ± 4.49 mm, $\overline{x}$ = 74.32 mm ± 4.24 mm respectively) (Table 3.13) (Figure 3.5).

Fruit Quality: Fuji apple diameter. Analysis of Fuji apple diameter detected significant differences ($F_{2,942}$= 22.05, $p<0.001$) between above canopy SSCDS and Airblast as well as in canopy SSCDS and Airblast. ($p<0.001$, $p<0.001$) No significant differences were detected between the in canopy SSCDS and above canopy SSCDS (p=0.99). Trees treated by the Airblast had significantly larger apples compared to both the above canopy and in canopy SSCDS ($\bar{x}$ = 68.68 mm ± 3.32 mm, $\bar{x}$ = 66.04 mm ± 3.54 mm, $\bar{x}$ = 66.0 mm ± 3.21 mm respectively) (Table 3.13) (Figure. 3.5)

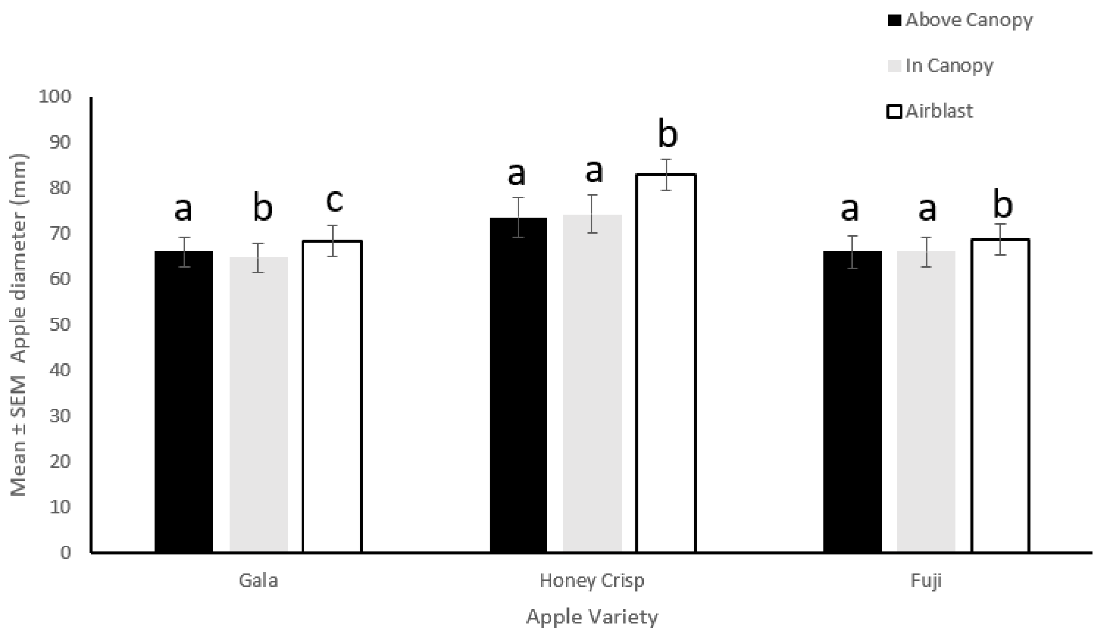

Figure 3.8 - Mean ± SEM apple diameter (mm) by variety and treatment. Apple diameter measured by caliper for each treatment within respective variety. Differing letters signify significant differences between treatments within variety at α=0.05.

Table 3.13 Mean ± SEM apple diameter (mm) Apple diameter in (mm) by variety and treatment. Differing letters signify significant differences between treatments within variety at α=0.05.

Variety	Treatment	Diameter (mm)	±SEM	
Gala	Above Canopy	66.09	3.21	a
	Airblast	68.40	3.40	b
	In Canopy	64.77	3.20	c
Honeycrisp	Above Canopy	73.61	4.49	b
	Airblast	83.01	3.46	a
	In Canopy	74.32	4.24	b
Fuji	Above Canopy	66.04	3.54	b
	Airblast	68.68	3.32	a
	In Canopy	66.00	3.21	b

Fruit Quality: Gala Apple Weight. Analysis of Gala apple weights detected significant differences ($F_{2,943}$= 48.08, p<0.001) between the above canopy SSCDS and in canopy SSCDS, above canopy SSCDS and Airblast, as well as in canopy SSCDS and Airblast (p=0.02, p<0.001, p<0.001 respectively). Trees treated by the Airblast had the heaviest apples compared to either the above canopy or in canopy SSCDS ($\bar{x}$ = 151.85 g ± 19.53 g, $\bar{x}$ = 135.03 g ± 17.69 g, $\bar{x}$ = 128.20 g ± 16.76 g respectively) (Table 3.14)

Fruit Quality Honeycrisp Apple Weight: Analysis of Honeycrisp apple weights detected significant differences ($F_{2,940}$= 223.10, p<0.001) between the above canopy SSCDS and Airblast as well as the in canopy SSCDS and Airblast, no significant differences were detected between the above canopy and in canopy SSCDS (p<0.001, p<0.001, p=0.66 respectively). Trees treated by the Airblast had significantly larger apples compared to the above and in canopy SSCDS ($\bar{x}$= 241.39 g ± 28.42 g, $\bar{x}$ = 170.71 g ± 24.92 g, $\bar{x}$ = 174.0 g ± 28.56 g respectively) (Table 3.14) (Figure 3.6).

Fruit Quality: Fuji Apple Weight. Analysis of Fuji apple weights detected significant differences ($F_{2,942}$= 24.47, p<0.001) between the above canopy SSCDS and Airblast as well as in canopy SSCDS and Airblast, no significant differences were detected between the above canopy and in canopy SSCDS (p<0.001, p<0.001, p=0.99 respectively). Trees treated by the Airblast had significantly larger apples compared to the above and in canopy SSCDS ($\bar{x}$= 148.74 g ± 20.18 g, $\bar{x}$= 132.19 g ± 20.53 g, $\bar{x}$= 132.34 g ± 18.34 g respectively) (Table 3.14) (Figure 3.6).

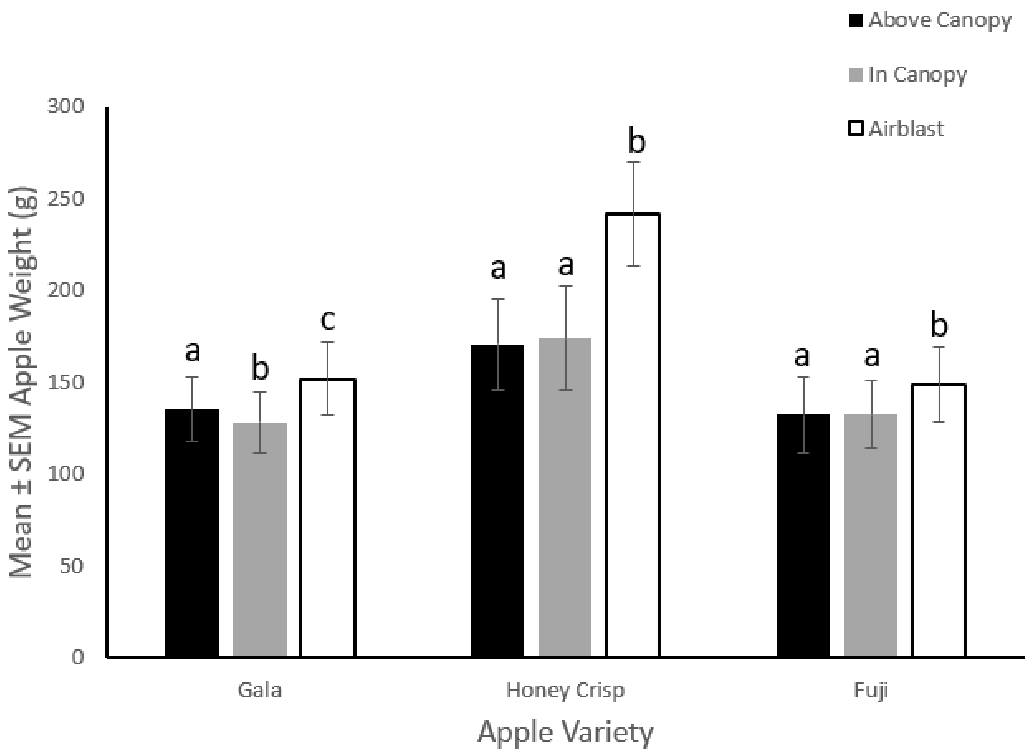

Figure 3.9- Mean ± SEM apple weight (g) by variety and treatment. Differing letters signify significant differences between treatments within variety at α=0.05. Apple weights were significantly greater in varieties treated by Airblast.

Table 3.14- Mean ± SEM apple weight. Apple weight in (g) by variety and treatment. Differing letters signify significant differences between treatments in variety at α=0.05.

Variety	Treatment	Weight (g)	±SEM	
Gala	Above Canopy	135.03	17.69	a
	In Canopy	128.20	16.76	b
	Airblast	151.85	19.53	c
Honeycrisp	Above Canopy	170.71	24.92	a
	In Canopy	173.99	28.56	a
	Airblast	241.39	28.42	b
Fuji	Above Canopy	132.19	20.53	a
	In Canopy	132.34	18.34	a
	Airblast	148.74	20.18	b

Fruit Quality: Gala Fruit Count. Analysis of fruit counts in Gala detected significant differences ($F_{2,87}$= 1.05, p<0.001) between the above canopy SSCDS and Airblast as well as the in canopy SSCDS and Airblast (p<0.001, p<0.001). A significantly lower number of apples were counted in trees treated by the Airblast compared to the above and in canopy SSCDS ($\bar{x}$= 61.93 ± 8.10, $\bar{x}$= 79.97 ± 11.49, $\bar{x}$= 86.87 ± 14.48 respectively).

Fruit Quality: Honeycrisp Fruit Count. Analysis of fruit counts in Honeycrisp detected significant differences ($F_{2,87}$= 32.64, p<0.001) between the above canopy SSCDS and Airblast as well as the in canopy SSCDS and Airblast (p<0.001, p<0.001). Trees treated by the Airblast had a significantly lower number of apples compared to the above and in canopy SSCDS ($\bar{x}$= 59.67 ± 10.26, $\bar{x}$= 105.67 ± 15.03, $\bar{x}$= 103.87 ± 18.89 respectively).

Fruit Quality: Fuji Fruit Count. Analysis of fruit counts in Fuji detected significant differences ($F_{4,87}$= 3.49, p=0.035) between the above canopy SSCDS and the Airblast (p=0.03). Trees treated by the above canopy SSCDS had a greater number of apples compared to the in canopy SSCDS and Airblast ($\bar{x}$= 59.67 ± 10.26, $\bar{x}$= 105.67 ± 15.03, $\bar{x}$= 103.87 ± 18.89 respectively).

Table 3.15 Mean ± SEM fruit count. Mean number of apples per tree by variety and treatment. Differing letters signify significant differences between treatments in respective variety at α=0.05.

Variety	Treatment	Count	SEM	
Gala	Above canopy	79.97	11.49	a
	In Canopy	86.87	14.48	a
	Airblast	61.93	8.10	b
Honeycrisp	Above canopy	105.67	15.03	a
	In Canopy	103.87	18.89	a
	Airblast	59.67	10.26	b
Fuji	Above canopy	120.83	15.2	a
	In Canopy	111.83	12.88	ab
	Airblast	103.43	15.34	b

Fruit Quality: Harvest yield. Analysis of the estimated metric tons of fruit harvested in Gala, Honeycrisp, and Fuji detected no significant differences between treatments in any variety ($F_{2,6}$= 0.045, p<0.66, $F_{2,6}$= 2.14, p<0.20, $F_{2,6}$= 1.5, p<0.30 respectively).

Table 3.16 Theoretical mean yield ± SEM metric tons per hectare harvested from treatment in variety. Mean Differing letters signify significant differences between treatments in respective variety at α=0.05.

Variety	Treatment	MT/Ha	±SEM	
Gala	Above canopy	35.45	4.37	a
	In Canopy	36.63	6.35	a
	Airblast	30.8	2.03	a
Honeycrisp	Above canopy	58.59	1.5	a
	In Canopy	58.38	1.98	a
	Airblast	49.86	5.51	a
Fuji	Above canopy	51.87	2.31	a
	In Canopy	48.08	0.74	a
	Airblast	50.28	1.16	a

Fruit Quality Conclusions: Fruit sizes in trees treated by the above canopy and in canopy SSCDS were similar in Fuji and Honeycrisp. All treatments were significantly different in Gala. Fruit sizes in trees treated by the above canopy and in canopy SSCDS are significantly different from the Airblast in all three varieties. Trees treated by the Airblast had the largest fruit in all three varieties (Table 3.14).

Fruit weights were greatest in trees treated by the Airblast. Significant differences were detected in all varieties between the SSCDS configurations and the Airblast, with apple weights heavier in Airblast treated trees. Airblast treated Honeycrisp apples had the heaviest weight of all combinations of treatments and varieties, approximately seventy grams heavier than weights associated with the above canopy SSCDS and in canopy SSCDS ($\bar{x}$= 241.01 g ± 3.46 g, ($\bar{x}$= 170.71 g ± 24.92 g, $\bar{x}$= 173.99 g ± 28.56 g respectively) (Table 3.14).

Fruit counts were greatest in trees treated by the above and in canopy SSCDS for Gala and Honeycrisp. In Fuji, trees treated by the above canopy SSCDS had greater fruit counts compared to the Airblast. In Fuji, the in canopy SSCDS did not statistically differ from either the above canopy SSCDS or Airblast. Honeycrisp mean apple counts in rows treated by the above canopy and in canopy SSCDS were almost double that of those treated by the Airblast ($\bar{x}$= 105.67 ± 15.03, $\bar{x}$= 103.87 ± 18.90, $\bar{x}$= 59.67 g ± 10.27 respectively) (Table 3.15).

Fruit size, weight, and count, in all varieties, differed significantly between the Airblast and at least 1 SSCDS configuration. Trees treated by the Airblast produced fewer, but larger, heavier fruit when compared to the SSCDS configurations. The larger, less numerous fruit identified in Airblast treatments and the smaller more numerous fruit in the SSCDS configurations suggests thinning applications were not as effective using either the above or in canopy SSCDS.

Both fruit counts and fruit weights were used to estimate the metric tons per hectare harvested in the fall of 2020. Even with the observed issues with thinning analysis of each variety detected no significant differences between treatments. Largest mean yields came from the Honeycrisp and Fuji varieties (Table 3.16). While the estimated weight of harvested fruit was greater this does not take into consideration saleable fruit. Pest damage and bitter pit disorder in Honeycrisp affect salability of harvested fruit. Honeycrisp apples, which are prone to bitter pit disorder, did have a higher incidence of bitter pit in trees treated by the Airblast, however this did not seem to have an effect on the estimated mt/ha of apples at harvest.

Apple thinning treatments are used to reduce the number of apples per tree in order to prevent crop overload and increase the abundance of larger, more marketable apples (Dennis 2020). Both SSCDS treatments had smaller apples for at least one variety compared to the Airblast treatment, suggesting poor thinning. One possible explanation for this is that the thinning agents were diluted or neutralized by residual liquids remaining in the SSCDS lines from a previous application. Since the dosage of the thinning agent was low in volume, its dilution by residual liquid may have altered its efficacy. Further evidence of inadequate thinning lies in the incidence of bitter pit disorder in Honeycrisp (Table 3.12). The thinning of apples to produce larger higher quality fruit also creates the conditions for bitter pit disorder (Rosenberger et al. 2004). Bitter pit disorder is at much lower incidence in fruit treated by both the above and in canopy SSCDS compared to the Airblast, a further indication of inadequate thinning in SSCDS treated trees. Future SSCDS projects should therefore evaluate thinning operations.

If the SSCDS is to be an adoptable technology, even with its other benefits, it must provide equivalent or better pest management efficacy compared to the current dominant technology. The above-canopy and in-canopy SSCDS differ in the coverage and deposition provided by each configuration with more homogeneous coverage and deposition across strata associated with the in canopy SSCDS and greater amounts of coverage and deposition higher in the canopy associated with the above-canopy SSCDS. Even with the differences in coverage and deposition the clean fruit and foliage assessed for the above canopy and in canopy SSCDS are near equivalent, with the Airblast sprayer. A vast majority of both fruit and foliage treated by the above and in canopy SSCDS as well as the Airblast were determined to be clean. Differences were detected in arthropod and disease damage, however these differences have more to do with varietal physiology like apple scab resistance and insect feeding preferences than treatments. Cultivars that are more susceptible to specific pests or diseases may require specialized emitters and emitter placement to properly treat pests with maximum efficacy. As stated by Owen-Smith (2019) There is concern regarding coverage to the underside of leaves treated by the SSCDS allowing for pathogens to go untreated. A possible solution for this would be to select chemistries that allow for the uptake and translaminar motion of pesticides (Klittich et al., 2013; Bostainan et al., 2012). Fruit quality by way of size, weight, and fruit count revealed that the SSCDS configurations require more optimization in the delivery of low volume active ingredients like thinning agents.

3.4. Conclusions

Moving forward, the SSCDS requires optimizations to ready it for consumer adoption. Optimization of chemical thinning application, operating pressure and volume, mass producible components, and effectiveness in multiple crops should be assessed. The system currently uses large volumes of liquid to bring lines to pressure and large air compressors to return liquids back to the tank. The addition of valves, reducing air requirements and reducing the amount of liquid required to run the system is a potential solution that requires exploration. Optimization of valving will also allow for investigation into injection molded or 3D printed parts allowing for easier installation in the field, as well as the production of affordable, fast, and easily replaceable parts should the need arise. As efficiencies in the usage of air and liquid distributions are explored re-evaluation of the application of thinners should be assessed as the small volume of thinning agents may have been affected by materials in the current system. Fundamental system specifications will most likely remain the same as the technology is adapted to other crops, however in order to move into other crops assessments should be made to optimize the SSCDS for the crops it is intended to serve. These changes will most likely be in the form of crop specific emitters and emitter placement.

The above-canopy and in-canopy SSCDS were able to provide equivalent season long pest management when compared to a fan assisted orchard sprayer. Fruit quality shows differences in fruit weight and size for Honeycrisp, with the Airblast treated rows producing larger fruit. This is due to higher apple counts in rows treated by the SSCDS configurations and is most likely due to ineffective thinning treatment. Bitter pit is present in blocks treated by the Airblast but not in the blocks treated by the SSCDS configurations again most likely associated with the ineffective thinning treatment leading to greater apple load. Adaxial and abaxial coverage provided by the in-canopy SSCDS was more homogeneous across the tree strata than the above-canopy SSCDS with the majority of the coverage on the adaxial surface for both above-canopy and in-canopy SSCDS, however data indicated this did not have significant effects on pest management efficacy. This research supports the idea that the SSCDS is a technology capable of effective year-long pest management of high-density apples.

Chapter 4 - Conclusions and Future Directions

The Solid Set Canopy Delivery System (SSCDS) is an alternative agrochemical spray system designed for trellised crops, such as high-density apple orchards and vineyards. High density training systems have become increasingly common, due to higher yields and because they are more efficient for pruning and harvesting. The axial-fan Airblast sprayer, developed for larger canopies, has remained the dominant agrochemical delivery system. This has led to the problem of off target drift occurring during agrochemical applications (Robinson et al. 2013; Holownicki et al. 2000). The SSCDS, optimized to treat the narrower orchard rows may be the solution to reduce off target drift as well as deposit more spray into the canopy. The goal of this thesis was to: Evaluate the SSCDS's potential to reduce off target drift compared to an axial-fan sprayer and to evaluate an over the canopy SSCDS's ability to provide agrochemical coverage and deposition, and adequate yearlong fruit quality and pest management.

Chapter 2 describes two off-target drift experiments comparing the SSCDS and axial fan Airblast sprayer applications. In 2017 I measured the off-target drift produced by an axial-fan Airblast sprayer and an in canopy SSCDS described by Owen-Smith (2019), adding an above canopy style SSCDS in 2018. My objectives were to determine the amount of off target drift produced by each technology, and where that off target drift was deposited. For these experiments, in row losses to ground, drift losses up to 12 m above the orchard, and drift losses up to 64 m downwind of the orchard were measured. I hypothesized that both the in canopy and above canopy SSCDS would produce the least amount of downwind and above ground off-target drift compared to a Rears PB533N Airblast sprayer. I also hypothesized that the off-target drift deposited to ground would be greater for the above canopy SSCDS and in canopy SSCDS compared to the Rears PB533N Airblast sprayer.

Losses to ground measured for both 2017 and 2018 were numerically similar between the in canopy SSCDS and axial-fan Airblast sprayer. In 2017 significant differences were detected between the in canopy SSCDS and axial-fan Airblast sprayer, however no significant differences were detected between sampler positions within either treatment (Figure 2.5, Table 2.3). This suggests that the position on the ground did not affect the amount of flux recorded in either treatment. In 2018's experiment the same methods of ground detection were used with the addition of a piece of filter paper added to the petri dish. This addition led to a greater collection of material and led to the detection of differences between treatments and positions (Figure 2.6, Table 2.4). In 2018 ground losses from the axial-fan Airblast and in canopy SSCDS had numerically similar deposition, the above canopy SSCDS depositing the greatest of the three. The larger droplets and higher flow rate per emitter associated with the above canopy

SSCDS were most likely the cause of this (Figure 2.3 B). The axial-fan Airblast and In canopy SSCDS had similar mean deposition values at every position, suggesting similar amounts of material were distributed below the canopy. However, it should be noted that the mean wind speed during axial-fan Airblast sprayer applications was considerably lower than booth SSCDS configurations (Table 2.2). The larger droplets provided by the above canopy SSCDS are likely more resistant to drift, making them more likely to stay near the orchard rows (Ferguson et al., 2015). For both SSCDS configurations deposition was numerically higher in upwind positions when compared to the Airblast sprayer, this may indicate the influence the fan has on particle movement with particles tending to move more downwind, or more readily influenced by wind.

Significantly higher vertical off target drift was produced by the axial-fan Airblast sprayer in both 2017 and 2018. All treatments followed the same pattern of greater drift near the ground and decreased with height. In 2017, percent flux as vertical drift peaked at 5% at 4 m for the in canopy SSCDS but was >25% at the same height for the Airblast sprayer (Figure 2.8, Table 2.5). This relationship was similar in the 2018 experiment with both SSCDS configurations greatest vertical off target drift at 1 m above ground (~10%) while the peak vertical off target flux for the axial-fan Airblast sprayer was ~66% at the same height (Figure 2.9, Table 2.6). Flux detected for both SSCDS configurations did not statistically differ and were <5% at all heights, nearing 0% at heights greater than 9 m. In contrast the axial-fan Airblast sprayer was near 30% flux for a majority of the heights sampled (Figure 2.10, Table 2.7). The pattern of off target drift ejected above ground suggests that the powerful fan of the Airblast sprayer is responsible for ejecting more material out of the orchard when compared to both SSCDS configurations.

Downwind off target drift was similar to vertical off target drift, SSCDS configurations produced significantly lower flux than the axial-fan Airblast sprayer. For 2017 and 2018 downwind drift deposited by the axial-fan Airblast sprayer was greater than both the in canopy and above canopy SSCDS for a majority of the distances sampled. In 2017 both the axial-fan Airblast sprayer and in canopy SSCDS peaked within the first 4 m downwind, the axial-fan Airblast sprayer at ~ 19% flux and the in canopy SSCDS at ~12% flux (Table 2.8). At 16 m downwind the percentage of flux deposited by the in canopy SSCDS dropped below 1%. At this same distance the percent flux deposited by the axial-fan Airblast sprayer was above 5%, and did not drop below 1% until 64 m downwind (Figure 2.11, Table 2.8). Downwind off target drift from 2018 was similar to 2017, also with a majority of the downwind drift produced by the axial-fan Airblast sprayer. Both the above canopy SSCDS and axial-fan Airblast sprayer produced ~20%-~30% flux as downwind drift at 0 m and 1 m downwind, the in canopy at these heights was between 5% and 10% flux. Flux measured for the above canopy SSCDS greatly decreased from 2 m to 4m downwind becoming near equivalent to the in canopy SSCDS, at greater than 2 m. In 2018's experiment flux measurements for both the above canopy and in canopy SSCDS were ~0% at greater than 8 m downwind. In contrast the axial-fan Airblast sprayer produced between ~20% to ~30% flux for the first 4m downwind, only dropping below 1% flux after 64 m downwind (Figure 2.12, Table 2.9).

The greatest flux produced by the above canopy SSCDS was measured nearest the downwind orchard row, the percentage of flux much greater than the in canopy SSCDS at that distance. The above canopy SSCDS produced much larger droplets compared to those of the axial-fan Airblast sprayer and in canopy SSCDS. These droplets with short trajectories made landfall not far from the orchard row. These larger droplets are most likely the reason for greater deposition in the first two meters downwind and why deposition further downwind was much lower, with similar values to the in canopy SSCDS. These larger droplets are less prone to drifting downwind and most likely made landfall within a few meters of emission. This is corroborated by ground loss, as deposition produced by the above canopy SSCDS was significantly greater than the in canopy SSCDS and axial-fan Airblast sprayer at the center and first two downwind positions, and numerically greater at a majority of the positions sampled (Figure 2.6, Table 2.4). In 2018 both the in canopy and above canopy SSCDS deposited their greatest flux near the orchard row, flux decreasing substantially within the first 4 m. This was not the case with downwind flux produced by the axial-fan Airblast sprayer, as flux values remained numerically similar for the first 4 m and much greater than those of the SSCDS configurations before gradually declining (Figure 2.12, Table 2.9). Similar patterns were present in the analysis of vertical off target drift for both years, with the flux produced by the SSCDS configurations greatest near the ground and steadily decreasing with height. The axial-fan Airblast sprayer again differs with much greater deposition at all heights and an initial increase in flux with height before a gradual decline.

Vertical and downwind drift data strongly suggests the axial-fan Airblast sprayer vectors spray droplets more prone to drift in comparison to the SSCDS. The axial-fan Airblast sprayer was responsible for greater vertical and downwind off-target drift both above and downwind of the orchard. This is further supported by ground loss data in which ground deposition produced by the Airblast sprayer was lowest, even with the lowest average wind speeds in 2018 further supporting that a greater amount of material is leaving the treatment area (Table 2.2). These findings are similar to Sinha (2019), in that, compared to an SSCDS, an axial fan sprayer was responsible for greater off target drift. Overall, the SSCDS produced much less off target drift that the axial-fan Airblast sprayer as it lacks the powerful fan shearing spray into fine droplets and vectoring them both above and downwind of the orchard.

Chapter 3 describes the comparisons of the overall horticultural performance of an above canopy SSCDS with an established, in canopy SSCDS and an axial-fan Airblast sprayer. Coverage and deposition were evaluated for the two SSCDS configurations, while pest management efficacy and fruit size and yield were evaluated for all three treatments. Coverage and deposition comparisons were made between the above and in canopy SSCDS while pest management efficacy and fruit quality assessment comparisons were made between the above canopy SSCDS, in canopy SSCDS, and axial-fan Airblast sprayer. The study objectives were to: 1) Assess coverage and deposition provided by the above and in canopy SSCDS. 2) Determine if the above and in canopy SSCDS could provide adequate pest management equivalent to an axial-fan Airblast sprayer 3) Determine if foliar agrochemical treatments provided by the above canopy SSCDS, in canopy SSCDS, or a axial-fan Airblast sprayer had differing effects on fruit count, fruit weight, or fruit size. I hypothesized that coverage and deposition values would differ by canopy strata, with the above canopy SSCDS responsible for greater coverage and deposition near the top of the canopy and the in canopy SSCDS providing more even coverage and deposition through the canopy. I also hypothesized that both the above and in canopy SSCDS would provide adequate season-long pest management equivalent to the axial-fan Airblast sprayer, with no differences in fruit quality between the treatments.

Spray coverage and deposition varied between the in canopy and above canopy SSCDS. Coverage differed by treatment, with the above canopy SSCDS providing greater coverage to the top third of the canopy while the in canopy SSCDS provided greater coverage to the bottom third of the canopy. In the top third of the canopy, both adaxial (top) and abaxial (bottom) surface coverage was greater in orchard canopy treated by the above canopy SSCDS, compared to the in canopy SSCDS. However, coverage in the bottom third of the canopy on both adaxial and abaxial surfaces was greater in trees treated by the in canopy SSCDS. This difference between the above canopy SSCDS and in canopy SSCDS is likely due to the positioning of the emitters. The above canopy SSCDS with emitters only present above the canopy and lacking the second emitter located within the canopy is likely why the top of the canopy and the adaxial face of samplers had greater coverage compared to the in canopy SSCDS. Analysis of deposition measurements indicated that applications by both the above and in canopy SSCDS did not significantly differ in any variety (Figures 3.5, 3.6, 3.7). Similar deposition across strata in high density apple orchards provided by the in canopy SSCDS were described by Owen-Smith (2019). Similar patterns of uneven coverage have been observed in previous studies (Owen-Smith et al. 2019; Owen-Smith et al. 2019; Sinha et al. 2020; Ranjan et al. 2021). This uneven coverage raised questions as to the SSCDS's ability to provide season long pest management. However, configurations similar to the in canopy SSCDS system, including this research have shown that an SSCDS can provide adequate pest management (Angello, & Landers, 2006; Owen-Smith et al. 2019; Owen-Smith et al. 2019; Sanhi et al. 2022; Koonter 2023).

A majority of the apples surveyed in all treatments and varieties were free of insect or disease damage, regardless of treatment for both years. A majority of the percentages of clean fruit detected in all treatments in all varieties were ~95% or > (Table 3.6). These findings are corroborated by the analysis of both arthropod and disease damaged fruit. In apples surveyed for arthropod damage a majority of the apples assessed were free of damage. A vast majority of the percentages of arthropod damaged apples in all treatments, in all varieties were below 1% (Table 3.8). The low percentages of diseased apples detected also suggests a majority of the fruit in all treatments and varieties were clean as most percentages of disease damaged fruit were < 5% (Table 3.10).

Foliar damage surveys suggest that a majority of the leaves in all treatments and varieties were free of arthropod or disease damage. A majority of the percentages of clean foliage detected in all treatments and varieties were found to be ~85% or > (Table 3.7). The surveys of both arthropod and disease damaged foliage showed that a majority of the foliage in all treatments and varieties were free of damage. The amount of foliage damaged by arthropods was low in comparison to the amount of clean foliage with a majority of the percentages of arthropod damages in all treatments and varieties < 5% (Table 3.9). The survey of disease damaged foliage also showed low levels of damage with a majority of the percentages of damage detected in all treatments and varieties < 10% (Table 3.11).

Overall, very little arthropod or disease damage was detected in either fruit or foliage. While differences were detected between treatments, no patterns emerged to suggest one treatment had a greater effect on pest management compared to another. A majority of the treatments in all varieties describe adequate pest management, and equivalency to an axial-fan Airblast sprayer. Similar findings are discussed in previous SSCDS research (Angello, A., & Landers, A. 2006; Owen-Smith et al. 2019; Owen-Smith et al. 2019).

Fruit diameter, weight, and fruit per tree were heavily influenced by treatment, with differences detected between the axial-fan Airblast sprayer and the SSCDS configurations. Fruit diameters measured in all varieties differed by treatment type, with significant differences detected between treatments in all varieties. In Gala and Fuji, apples treated by the axial-fan

Airblast sprayer were largest. Honeycrisp apples treated by the axial-fan Airblast sprayer and in canopy SSCDS were largest. (Table 3.13). Fruit weights were similar to fruit diameter in that weight was dependent on treatment. Significant differences between treatments for all varieties were detected, with apples treated by the axial-fan Airblast sprayer being the largest. Honeycrisp apples, treated by the axial-fan Airblast sprayer, were twice as heavy, ~70 g larger than apples treated by the SSCDS configurations (Table 3.14, Figure 3.9). Fruit counts also appear to have been affected by treatment. Significant differences between treatments in all varieties were detected. Gala and Honeycrisp trees treated by the axial-fan Airblast sprayer had a significantly greater number of apples in comparison to the SSCDS configurations (Table 3.15). Honeycrisp trees treated by the SSCDS configurations had twice as many apples as those treated by the axial-fan Airblast sprayer. Higher fruit counts, smaller diameter fruit, and lower fruit weights in trees treated by the SSCDS configurations indicate ineffective apple thinning provided by the SSCDS.

Bitter pit disorder was found exclusively in Honeycrisp apples; its incidence in axial-fan Airblast sprayer treated trees was four times higher than in those treated by the SSCDS configurations (Table 3.12). Bitter pit can be brought on by vigorous tree growth or excessive fruit size (Biggs et al. 2015). Higher incidence of bitter pit along with fewer, larger apples in trees treated by the axial-fan Airblast sprayer is further evidence of ineffective thinning provided by the SSCDS configurations. Trees treated by the SSCDS produced significantly more, and smaller apples, this correlates with reduced incidence of bitter pit in SSCDS treated trees compared to the effective treatment provided by the axial-fan Airblast sprayer. The smaller, more numerous apples did not seem to have an effect on the theoretical harvest tonnage, as no statistically significant differences were detected between treatments in all varieties (Table 3.16). However, this does not take into account apple quality.

Overall, my research demonstrates that the SSCDS produces significantly less downwind and vertical off target drift when compared to an axial-fan Airblast sprayer in a high-density apple orchard. Additionally, two configurations of the SSCDS, the above and in canopy, were able to provide season-long pest management equivalent to a axial-fan Airblast sprayer. This is a significant finding because the above canopy SSCDS configuration removes emitters from the canopy decreasing the chances of emitter damage or occlusion due to tree growth, pruning, and training. This research provides further evidence that the SSCDS is an effective alternative spray technology better tailored to high density cropping systems compared to large fan driven implements.

The SSCDS has the potential for use in multiple crops, especially trellised row crops. The SSCDS was developed using technology intended for greenhouse irrigation, and with the narrower spaces present in a greenhouse, further research into greenhouse applications would be a logical next step (Owen-Smith, 2017). Cropping systems similar to a grape vineyard or high-density apple orchard may also benefit from an SSCDS, with research concentrating on optimizing emitters and emitter placement in order to maximize coverage and deposition in each crop. Due to the large volume of air needed to purge the system and agrochemical required to pressurize the system, research into control valving to reduce the required air and reduce waste agrochemical will be a necessary next step. Further research into the potential benefit of reduced fossil fuel use and reduced soil compaction compared to large tractor drawn implements should also be conducted.

4.1. Future Outlook

The fully optimized SSCDS will not only provide reduced off target drift and pest management but will be utilized as a fully automated system. The fully optimized system will provide the benefits that come with drift reduction such as worker safety and environmental protection. Automation will also provide worker safety and reduce labor by removing the operator from the treatment area. Automation may also provide the benefit of reduced soil compaction.

To reach this optimized system, research is required into some of the fundamental functions of the SSCDS. Calibration of fruit thinning and fruit retention treatments will be required as inefficiencies were detected in this research. Fault detection will also be paramount in the technology moving forward as thousands of emitters will be in use. The SSCDS needs excess liquid and large volumes of air to operate, removing waste and developing a more efficient system is required. Finally, research into the SSCDS's full automation would be a logical next step, allowing for numerous benefits.

As a drift reducing technology, the SSCDS could be a powerful tool in the future. As shown from this research and other work reviewed herein, the SSCDS reduces off-target drift which may allow it to fall under a category of equipment known as Drift Reducing Technology (DRT). As pesticides come under greater scrutiny, any off-target exposures may lead to the banning or further restrictions on usage. Future regulations may ban certain chemistries from certain application equipment. However, with its marked drift reduction, an SSCDS could serve as an alternative, or even the only option for some products.

Aside from pest management applications, the SSCDS must also be able to provide chemical fruit thinning and fruit retention. Thinning was attempted using the SSCDS utilizing a protocol developed for the axial-fan Airblast sprayer, however this failed. Due to the structure of the SSCDS evaluated in this research, it is possible that the thinning agents used were in such low volume that residual chemical remaining from a previous spray either diluted or interfered with the actives in the thinners. Chemical thinning is difficult, and success depends on the right mixtures of thinning agents and can differ by apple variety, rootstock, weather, tree condition, bee activity, temperature, etc. (WSU 2023). For the SSCDS to succeed at thinning, it will require testing to develop a thinning program specific to both the apples and the SSCDS treating them.

The development of a fault detection procedure is one of the most important pieces of research remaining. Orchards spanning hundreds of hectares could require the deployment of tens of thousands of emitters. Each emitter has the potential to be dislodged (spilling more than the prescribed amount of material) or occluded (no material emitted). This could lead to the overdosing or underdosing of agrochemical leading to wasted agrochemical or the proliferation of pests.

Fault detection could come in the form of pressure sensory or thermal detection. Pressure sensory has the limitations of needing to place several pieces of equipment into the field and needing to detect minute pressure changes within the system. Upon evaluation of this, off the shelf components were not able to detect changes based on single occluded or removed emitter. It is also very possible that if sensory equipment sensitive enough to detect a malfunctioning emitter is used, that pressures incurred by the heat of the day will interfere.

The thermal approach used thermal imagery taken from above the orchard via drone. Both dislodged and occluded emitters were successfully detected during an application of water. Fault detection in the above canopy SSCDS was much more successful than attempts with an in canopy SSCDS. The emitters within the canopy were not detected from above. Future research into thermal fault detection would make use of an above canopy SSCDS and numerous automated drones. A calibration standard for thermal imaging would need to be developed as the detectable differences between ambient leaf temperatures and applied water temperatures will change with crop type and environment.

Research to eliminate the need for wasted agrochemical and the large air requirements of the SSCDS will also need to be conducted. The SSCDS utilized in this thesis requires a filling stage where all the lines are filled at low pressure. Not all of the liquid in this filling stage is emitted and is lost as waste. Ultimately, air is forced through the system driving excess waste liquid back to the tank. Due to the compressibility of air and the large volume of the SSCDS, the amount of compressed air required to achieve clearing is often provided by an industrial size air compressor. This large air compressor may be required to run for several minutes depending on the size of the SSCDS.

Current solutions for reducing waste and the need for large volumes of air, segment the system into smaller chambers. Two of the systems explored are the “canister” as described by Ranjan (2021) and an inline segmentation being explored by Application Insight LLC and MSU Technology. The inline system uses a series of valves to allow liquid to escape through emitters during the application of compressed air, but seals when no liquid is present reducing the consumption of air. Further research into this particular set of optimizations is best suited for engineers specializing in both spray technology and hydraulics/pneumatics.

The fully realized SSCDS is an ecosystem of automated components. This system would be a combination of sensors and programming controlling spray application timing, dosages, products, and thermal fault detection. The system would either be operated from a central location where the pump, compressor, and agrochemical tank are directly attached to the entire SSCDS installation, similar to Sinha (2020). Or the system will be operated by a mobile automated compressor, pump and agrochemical tank which drives up to multiple sets of the SSCDS in the orchard.

Sensory equipment could time sprays around rain events as well as indicate faults during automatic thermal scans. This equipment could also mix the appropriate agrochemicals and apply them all based on preprogrammed scheduling, reactions to the environment, or commands from the user. This system will most likely be operated by all three.

The benefits of an automated system are safety, reduced labor, as well as reduced soil compaction. Automation removes the user from the area being sprayed. The removal of the operator from the field not only reduces the chances for pesticide exposure but reduces labor. For climates like Michigan’s, numerous pesticide applications are required, automation removes the need for a laborer to drive an implement into the orchard. This also removes the need to drive a heavy farm implement several times into the orchard rows, thus reducing the chances of soil compaction.

The fully optimized SSCDS has a range of benefits, including drift reduction, and pest management but also the technology can readily be integrated into an automated sensor array. This automated system would provide greater worker safety, reduce labor, as well as reduce soil compaction. As research continues this promising technology may yet find its way into several new crops and cropping systems.

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