VARIATION OF SPRAY DEPOSITION WITHIN CITRUS GROVES DUE TO WIND CONDITIONS

By

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I dedicate this work to my mom who has been waiting for my graduation to see me; to the soul of my father who had said “if I knew that Ahmed will be away from us for more than three years, I would not let him go”; to my wife, Noor who has been fully supporting; to my daughters and son, Maysra, Zinah, Usur, Maria, and Muhammad, the beautiful flowers in my life; to my brothers and sisters who always pray for my success

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In citrus groves, pesticides are usually applied with the assistance of air-jets produced by air-blast sprayers. The air-jet transports the spray droplets to the tree canopy and helps them penetrate within the canopy. The movement of the air-jet and spray droplets is normally affected by the ambient wind; hence, the wind could change the deposition distribution. The main objective was to quantify the variability in the deposition due to the ambient wind. The research reported here involved four experiments: a) wind variability data collection, b) laboratory test of wind effect on the movement of a simulated air-jet and its deposition, c) experimental study under field conditions in an open area (no trees), and d) spray test in a citrus grove.

The objective of the wind variability experiment was to compare data recorded by the Florida Automated Weather Network (FAWN) (outside the grove at 10.0 m above the ground) with the measurements made within a citrus grove (GROVE) at different heights. Wind speed and direction within the grove and those outside were highly correlated. However, their averages were different. Within the grove, wind velocity reduced as moving down along the canopy height. At the same time, wind velocity of

1.5 m/s or less, recorded at 10 m height, resulted in almost zero wind velocity at lower heights.

In the laboratory test, the objective was to determine the effect of simulated wind on the movement of a simulated air-jet of an air-blast sprayer and the droplet trajectory. A piezo-electric nozzle droplet generator was used to generate different spray droplet spectra. Deionized water was used as spray liquid. The velocity of the air-jet normally reduced as it moved away from the outlet. However, applying 1.2 and 2.2 m/s crosswinds further reduced the air-jet velocities measured at 85 cm from the outlet by 11% and 20%, respectively. Wind effects were related to the wind direction. Perpendicular crosswind resulted in the highest velocity reduction. The high-velocity wind resulted in the highest deflecting distance of 12.3 cm for the air-jet discharged from small outlet. Increasing the air-jet outlet size mitigated the wind effect and reduced the deflection to 8.1 cm. The smallest droplet size was deflected more than the largest droplets. A crosswind of 2.2 m/s reduced the overall deposition on the intended target by 32%. However, increasing the droplet size mitigated the wind effect.

In both open area and citrus grove tests, a tracer of Pyranine 10G was applied using an air-blast sprayer driven at 2 and 6 km/h in 2 directions and using 2 Albuz ATR Lilac and Blue nozzles. In the open-area test, deposition was sampled on artificial targets from three distances at each side of the sprayer. However, citrus leaves, collected from first and second tree row on the right side only of the sprayer, were used to sample the deposition in the citrus grove test. Fluorometric analysis was made of the samples from the two tests to determine the deposition. Leaf area measurements were also made. In the open area test, increasing the crosswind increased the deposition downwind at all the distances. However, it increased the deposition at 3 m upwind only and decreased it at the 6 and 9 m. Increasing the wind speed increased deposition variability upwind. At 9 m upwind, targets collected almost zero droplets. Increasing the parallel wind slightly decreased the deposition on both sides at all distances. However, driving in two opposite directions under windy conditions increased the deposition at tailwind and reduced it at headwind.

Ambient wind conditions within citrus groves were significantly different from those outside the groves. Wind reduced the velocity of a simulated air-jet by about 20% and deflected its direction by about 12 cm, measured at 85 cm from the outlet, and hence reduced the overall deposition average by 34%. Under field conditions, the deposition downwind was twice as much as the one collected upwind. Also, the ambient wind significantly reduced the overall deposition collected on both sprayer sides. Thus, spraying under windy conditions will result in a non-uniform deposition between the two sides of the sprayer and between the two directions of the sprayer travel.

CHAPTER 1
INTRODUCTION

Controlling pests in citrus groves is of utmost importance for the growers and researchers. To accomplish that ultimate goal, the tree canopies are usually sprayed with different pesticides. In Florida, citrus trees grow and develop to about five to six meters high and about four meters wide. Applying the pesticides directly (no air-assistance) onto these large canopies will deposit most of the materials on the outer sides of the canopy and reduce the coverage uniformity, especially at the top and inner parts of the canopy. Thus, transporting the sprayed materials to the canopy and helping them to penetrate within the canopy and contaminate the whole tree, will relatively improve the pest control in citrus. An air stream was found to be very useful in moving the spray droplets to the whole tree and help them penetrate within the canopy. Therefore, air-assisted sprayers became the most popular equipment used in citrus applications (Cunningham and Harden, 1998a). The sprayers use axial-flow, cross-flow or centrifugal fans to discharge airflow and application materials towards the whole tree canopy. Moving the airflow with the spray droplets along the distance to the top parts of the canopy will reduce its energy and velocity and hence, make it more vulnerable to the wind effect. In addition, the top parts of the canopy are relatively denser than the lower parts; therefore, the airflow needs to be able to penetrate within them. Wind could reduce the velocity of the air-jet and, hence reduce its efficiency to transport the pesticide droplets to the targets and therefore reduce the efficacy of pest control. Wind could also shift the droplet direction. Any portion of the pesticide that does not reach the intended target could be an environmental hazard in addition to be wastage of the material. Therefore, pesticide losses should be minimized as much as possible. Wind could come at any speed and from any direction. At the same time, it cannot be avoided completely during the spray application. Due to the absence of suitable wind conditions during most applications and the urgency to control a pest outbreak, sprays are often applied in relatively windy conditions (Reichard et al., 1979). Thus, using the air-assisted sprayers in citrus application under windy condition is valid, but handling the situation in a way that could minimize the wind effect is of concern.

1.1 Problem Statement

In citrus groves, pesticides are usually applied by different types of air-assisted sprayers. The movement of the sprayer air-jet and the trajectories of spray droplets are influenced by the ambient wind. Therefore, it is advised to avoid spray when wind speed is greater than 4.5 m/s (Salyani, 2013). However, specifying how a wind speed range limits wind effects on the spray is still not established. Wind directly affects the air-jet movement. A crosswind could shift the air-jet direction to about 0.5 m away (Endalew et al., 2010). Changes in the air-jet direction will directly reduce the deposition on the intended targets due to changing the spray droplet trajectories. Wind that affects the air-jet direction will also reduce its velocity and hence, fewer amounts of droplets will reach the targets. Deflected spray droplets could be redirected either to another target (causing varied deposition distribution, and hence poor biological efficacy) or to sensitive off-targets (creating environmental contamination issues). In both cases, the droplet deflection needs to be minimized. Regardless, wind effects on the air-jet depend on its speed and direction (Fox et al., 1985).

Wind conditions within the canopy height usually differ from those above the canopy level or outside the grove to some extent. The tree canopy could reduce the wind velocity to about 1% to 5% of those recorded 61 m above the canopy level

(Baynton et al., 1965). In general, wind conditions are given as averages for some periods of interest. For example, Florida Automated Weather Network (FAWN) reports wind conditions based on a 15-min intervals. However, the conditions may vary substantially within the reporting period. For example, within 20 s only, chosen randomly from a spray time, wind speed fluctuated between 2.7 to 8.2 m/s (Koch et al., 2005). These momentary changes in wind conditions might become inconspicuous by the data averaging. However, in field spray treatments, sprayer applications face such variations in wind conditions, which may alter the droplet trajectory and hence, affect the deposition distribution to some extent.

Wind conditions usually are measured at about 2- and 10-m heights (ASABE Standards, 2009) outside the grove. However, knowing these conditions within the canopy height might be more relevant to understand the deposition variability on canopy. Droplet size directly affects its moving speed and trajectory (Bagherpour et al., 2012) which could lead to changes in the deposition. The sprayer airflow also affects the deposition on the canopy (Farooq and Salyani, 2004). Thus, different sprayer designs (diversity in the air-jet volumes, velocities, and directions) might react differently towards the same wind condition. Examining these variables under windy conditions will be useful for sprayer design and for variable-rate sprayers.

1.2 Dissertation Objectives

The main objective of this study is to quantify the variability in the spray deposition in citrus due to the ambient wind. To accomplish that goal, the following sub-objectives were established.

1. Characterize the variability of ambient wind in citrus groves.
2. Determine wind condition effects on the air-jet movement toward targets.

3. Determine the effects of different air-jet outlets and droplet size spectra on the variability of spray deposition under different wind conditions.

4. Quantify the deposition variability of air-assisted sprayers under field conditions.

CHAPTER 2
LITERATURE REVIEW

Factors Affecting Spray Distribution in Citrus

Air-blast sprayers are the most popular equipment used in Florida citrus applications. They use different fan types to discharge airflow to transfer the spray droplets to the tree canopy. The deposition coverage on the top zones of the canopy is expected to be less (Derksen and Breth, 1994) because they are denser than other canopy parts and also far away from the sprayer outlet. As a solution, a sprayer that uses assisted air-tower to discharge airflow and materials relatively horizontally towards tree canopy along the canopy height is also developed and used in citrus applications. Increasing the travel speed of these sprayers will increase their productivity and hence, save time and labor. In this case, the spraying volume rate must be adjusted to compensate for the speed changes by maintaining a specific volume rate that is recommended for a specific area unit. Changing the volume rate is usually done by using different nozzles, increasing the number of active nozzles, or adjusting the system pressure. In addition, to maximize the spray uniformity, the sprayer needs to maintain a constant distance from the tree canopies. This task is related to the operator experience and the grove conditions such as the uniformity of tree sizes and the inter-row distances. Thus, many operating variables, field characteristics, weather conditions, and operator practices affect the whole outcomes of the spray application.

2.1 Wind Condition

In general, due to the relatively large size and high density of citrus tree canopies, agrochemicals are applied with the assistance of some air-jet from air-carrier sprayers (Cunningham and Harden, 1999; Stover et al., 2004a; Salyani et al., 2007).

The air-jet transfers spray droplets onto the canopy and helps them to penetrate within the canopy. Droplet transport towards and onto the target canopy is normally influenced by wind velocity and direction as wind affects the movement of the sprayer air-jet (Khdair et al., 1994). In citrus pesticide applications, the off-target movement of spray droplets could result in contamination of air, soil, and water resources. In a study of citrus spray mass balance, Salyani et al. (2007) found that spray losses (spray drift and ground deposition) could amount to about 26% of the total discharged material.

In a laboratory study, Fox et al. (1985) found a reduction in the air-jet velocity and deflection in its direction due to the crosswind effect. The distortion of the air-jet may result in non-uniform spray deposition and poor biological efficacy. In a study of the effects of wind conditions on deposition and drift from aerial applications, Bird et al. (1996) and Fritz (2006) found that wind velocity is the most influential factor on drift. Traveling distance of drifted droplets varies based on the wind velocity. Fritz (2004) also found wind velocity to be a significant factor affecting spray ground deposition and its airborne concentration. Furthermore, Thistle et al. (1998) and Salyani (2000b) found that wind direction is the most important factor affecting spray efficiency. However, Hoffmann and Salyani (1996) found no significant effect of the wind conditions on the spray deposition on citrus trees when they used the weather conditions (air temperature, relative humidity, wind velocity, and wind direction), recorded at one location within the study field, as co-variables.

Theriault et al. (2001) studied the potential of recovering spray droplets on intended targets in citrus application. The sprayer moved at 4.8 km/h in two opposite directions, parallel to wind blowing at 3.9 to 5.0 km/h. The results in an open area (no trees) showed higher spray recovery (44.5%) when sprayer moved downwind as compared with a recovery of 34.9% upwind. However, the driving direction had no effect on the recovery within the citrus trees. In addition, they found higher variability in the deposition when driving upwind than downwind.

Results of a study conducted by the Spray Drift Task Force (1997) showed that increasing crosswind velocity from 2.0 to 5.4 m/s increased the downwind spray deposition of an air-blast sprayer tenfold beyond the fifth row of apple trees. Although the trees were in dormant stage and had no foliage, the results gave an indication about wind effects. In a wind-tunnel study, Khdair et al. (1994) investigated the roll of the sprayer air-jet on deposition characteristics of charged plant canopies under different wind conditions. Their results showed a significant reduction in deposition by increasing wind velocity. For instance, increasing wind velocity from 2 to 4 m/s reduced the deposition on the top surface of the targets by about 71%.

Endalew et al. (2010) found a reduction of 2.0 m/s in the sprayer air-jet velocity, measured at 2.3 m from the air-jet outlet due to a crosswind (90°) of 5 m/s . The same wind deflected the air-jet direction toward its direction by 0.5 m at the same measuring distance. Air-jet was not only affected by the wind speed, but also, by its direction. Fox et al. (1985) examined the behavior of a simulated air-jet under wind of different directions. They found more deflection in the air-jet direction, measured at 20 cm from its outlet, due to a crosswind of 135°(measured from the air-jet direction),than a perpendicular wind (90°).

The presence of the tree canopy changes wind conditions between outside and inside the grove to some extent. These condition differences will be more significant at different measuring heights within the canopy. Fons (1940) studied the wind velocity and direction at different heights within open grassland, brush, and moderately dense ponderosa pine areas. The vegetative coverage on these sites was approximately 0.15, 1.40, and 21 m above the ground, respectively. The results showed a linear relationship between velocities at any two measuring heights. However, different heights had different linear slopes and intercepts. Baynton et al. (1965) studied meteorological conditions above the canopy of a tropical forest and within it. They found that wind velocity within the canopy (based on half-hour averages) reduced to about 1% to 5% of the velocity recorded at 61 m above the ground. Wind direction averages recorded at the 61- and 45-m heights at 2 locations (1100 m apart) were in good agreement (R^2 = 0.95); however, they changed randomly within the canopy height. Renaud et al. (2010) compared climatic conditions between open site and below canopy over a 10-year period. They found highly significant reduction in the wind velocity below canopy as compared with the open-site measurement; however, the differences between the wind velocities of the two sites were not correlated with the canopy characteristics (height and density).

Under field conditions, wind speed is never constant, it fluctuating even over short time intervals. For example, during 20 s, chosen randomly from the spray time, wind speed changed between 2.7 to 8.2 m/s (Koch et al., 2005). Such momentary changes in wind conditions may alter the droplet trajectory and hence, change the deposition distribution. In addition, they make it difficult to find a significant relationship between wind conditions and the deposition variability (Nordbo et al., 1993).

Although it is well documented that wind affects the spray deposition in orchard applications, it is challenging to quantify these effects (Stover et al., 2003; Koch et al., 2005). Moreover, conducting field experiments is expensive and results in higher levels of uncertainty due to the variability in field conditions (Xu et al., 1998). In addition, using some procedures to reduce the variability will be time consuming (Salyani, 2000a). Field experiment also could be more expensive.

2.2 Ground Speed

The productivity of the sprayer is directly affected by its ground speed. However, increasing the ground speed needs more investigation, especially about the interaction of speed with the meteorological conditions and their effects on spray deposition (Hoffmann and Salyani, 1996). Therefore, the effects of this variable are under investigation by many researchers (Salyani and Whitney, 1990; Cunningham and Harden, 1998b). Cunningham and Harden (1998b) found that spray deposition was not affected by changing ground speed between 1.6 and 3.4 km/h. These results were in agreement with results of a study by Salyani and Whitney (1990) when they changed ground speed of an air-blast sprayer from 1.6 to 6.4 km/h and found no significant effect on the spray deposition on the leaves of citrus trees. However, these changes in the ground speed significantly increased the deposition variability (Salyani, 2000b) and reduced canopy runoff (Cunningham and Harden, 1998b). A study by Whitney et al. (1988) to quantify the copper deposition on the two sides of citrus leaves showed that mean copper deposited on the upper side of the leaves was significantly affected by changing the ground speed from 1.6 to 3.6 km/h. Conversely, the mean copper deposition on the lower side was not affected.

In spray applications, using air blast sprayers, a ground speed of 0.8 to 4.8 km/h (0.5 to 3.0 mph) is considered ideal (Farooq and Salyani, 2004; Hall and Rester, 2012; Rester, 2012). However, Salyani and Whitney (1990) used a ground speed of 6.4 km/h (4.0 mph) without adverse effects.

To minimize the drift from an air-blast sprayer, the volume rate of 2000 l/h and sprayer ground speed of 4.0 km/h were recommended to be used in Florida citrus application (Salyani, 1995). Changing the travel speed of the sprayer could affect the deposition through altering the droplet movement within the canopy. Reducing the speed to 2.85 km/h resulted in the highest movement speed of the droplets through the first tree row (Salyani et al., 2009). However, these effects significantly interacted with volume rate. While increasing the ground speed of the sprayer at low volume rate increased on–canopy deposition and slowed down the droplet movement through the first tree row, the deposition did not increase at high volume rate (Salyani et al., 2009).

Changing the ground speed did not affect the deposition efficiency, significantly. However, the interaction between the ground speed, disc size, and number of nozzles had a significant effect on the deposition (Salyani, 2000b). By assuming an equality of volume rates (an average of 866 L/ha), combinations of 6 nozzles at 1.6 km/h, 12 nozzles at 3.2 km/h, and 18 nozzles at 4.8 km/h significantly reduced the deposition efficiency to 27%, 25%, and 22%, respectively. However, at the average volume rate of 2500 L/ha, the trend was perfectly reversed.

When it comes to the use of precision technology in spray applications, using a laser scanner to characterize tree canopy structure was affected by changing the ground speed. At high speed (3.2 km/h), tall branches of the trees were not sensed by the scanner, which underestimated the height measurements of tall branches at ground speed of 1.6 km/h (Salyani and Wei, 2005). In this technology, the sprayed materials and airflow of the sprayer are determined based on the canopy volume sensed by the scanner. Thus, changing sprayer ground speed will indirectly change the deposition through its interaction with other variables.

2.3 Airflow

Applying spray materials without air assistance, using a tunnel sprayer, deposited most of the dye on the top surfaces of leaves, particularly in the periphery of tree canopy and resulted in the least uniformity (CV=137%) of the deposition (Peterson and Hogmire, 1994). Due to the concern of reducing the applied spray volume, Matthews (2000) reported about the ability of reducing spray volume by using airflow to transport spray materials into the plant canopy. Using an air-assisted sprayer could save about 90% of the spray materials that are applied using a hydraulic sprayer. In addition, the distance that can be reached by large droplets, using air-assisted sprayers, is directly affected by the strength of the airstream and the initial trajectory of the droplet (Matthews, 2000). Therefore, optimizing the airflow rates of the sprayer is highly recommended.

Salyani and Farooq (2003) found that air volume significantly affected the spray deposition on the leaves of citrus trees in locations close to the sprayer outlet but the deposition was not affected in the farther locations. Overall, they found no significant differences between different airflow rates on the spray penetration and the deposition. However, they recommended using sprayers with small airflow capacities to spray small canopy trees. In another study, Farooq and Salyani (2004) found an increase in the deposition at the near side of the canopy by reducing the airflow. Whitney and Salyani

(1991) found that using conventional air-blast sprayers resulted in mean copper deposition higher than that for air-tower (Curtain) sprayers. This difference might be due to the differences in the airflow rates and the initial airflow velocities of the different sprayers.

By comparing the deposition on both sides of the leaves, Peterson and Hogmire (1994) found almost no deposition on the lower surface of the leaves, using spray materials without air assistance, especially in the center of the tree canopies. Brazee et al. (1981) stated that airflow should be enough to deflect foliage and to convey and cause impingement of droplet on the target. Pai and Salyani (2008) found differences in the air penetration across tree canopies by changing the airflow rates from 1.9 to 7.6 m^3/s. They also found a reduction of 37% in the off-target mean deposition, at high application rate by reducing airflow rate from 7.6 to 1.9 (m^3/s).

Changing the velocity and volume of the airflow to match the canopy characteristics is one of the advanced methods to improve the sprayer efficiency (Chen et al., 2012). However, changes in the airflow volume or its speed to improve the deposition could make it more vulnerable to the wind effects. Fox et al. (1985) found that a narrower outlet deflected more than a wider one due to the crosswind when they had the same power at the outlet. However, the study was conducted with a reduced-size modeled sprayer (1/12 scale). Spray deposition within the tree canopy is directly affected by the sprayer airflow. The airflow should have a potential to move the leaves so they could get deposition from both sides. However, the airflow needs to match the tree canopy size even at different growth stages (Landers, 2008). Thus, the airflow volume or speed should be large enough to transport the droplets and help them to penetrate within the canopy because any additional volume or speed will consume more energy and may not improve the deposition.

2.4 Spray Height

Spray efficiency is a function of spray conditions, sprayer parameters and their adjustments, and characteristics of tree canopy such as shape, density, and height. Canopy height plays an important role in this analysis as one encounters tall trees (5.0 to 6.0 m) resulting in low coverage in the top zones of the canopies (Derksen and Breth, 1994), especially when low profile sprayers are used. At the same time, discharging spray materials from a low level towards the upper parts of canopy might result in less coverage uniformity on the whole canopy. Furthermore, using high velocity airflow to move the spray droplets to the top of the canopy will increase drift losses (Salyani et al., 2006). A study by Stover et al. (2004b) showed that about $143/ ha of spray materials is lost, annually. Salyani et al. (2006) found that discharging spray materials from a low zone (vertically) to the canopy tops resulted in more drift over the canopy zone and lesser amount of droplets that crossed to the other tree-side. However, spraying materials horizontally from different heights using the air-tower sprayer reduced the drift but increased the deposition on the outside of the trees of the second row. When it comes to compare spray losses as drift, applying spray materials from different heights resulted in the lowest drift above the tree zone and reduced the run-off losses significantly as compared with radial spraying from a low zone (Cunningham and Harden, 1998a).

Comparing two air-assisted sprayers, Cunningham and Harden (1998a) found that delivering spray horizontally from a tower sprayer along the canopy height has more uniform deposition at different canopy heights of citrus trees. In contrast, the deposition from the low profile sprayer significantly decreased in the tree canopy as the tree height increased. They reported that the highest spray deposited on leaves at the top zone came from a sprayer with tower of 5 m height. Thus, not only the deposition amount but also the spray uniformity was affected by spray discharging height.

Whitney and Salyani (1991) compared deposition characteristics of conventional air-blast and air-tower sprayers and their results were not in agreement with previous results. They showed less mean spray deposition of the air-tower than conventional sprayer in orange trees. However, the difference was not significant in grapefruit trees. Their results also showed more uniformity of the deposition of conventional sprayer than the deposition of the air-tower sprayer. These results were attributed to the differences between these sprayers in their distances from the canopy and the variation of airflow rates and velocities.

2.5 Spray Distance

Different sprayers may have different distances between their discharging outlets and the farthest side of the sprayer frame. This distance, in addition to the operator experience, the tree canopy shape, and grove conditions, will vary the distances of spray applications. Applying spray materials from relatively close distance toward the tree canopy resulted in a maximum deposition on target (Salyani, 2000b) and reduced the off-target drift losses . However, a very short distance between sprayer outlet and the target might not give enough time to the spray materials to be spread and mixed properly within airstream and also increase runoff (Salyani, 2000b). Therefore, maintaining a specific distance between the sprayer and the target is required for efficient application. Salyani (2000b) found a significant decrease in the deposition by increasing the distance from the sprayer. A laboratory examination of deposition efficiency on moved targets, placed at three distances (26, 61, and 102 cm) from a droplet generator, showed that the highest efficiency was achieved by targets placed on the short distance of 26 cm (Salyani, 1988). A study by Whitney and Salyani (1991) showed a significant reduction in the deposition mean by increasing the distance inside the tree canopy. A reduction of 23% in the deposition was recorded at 0.6 m inside the canopy from the farthest side compared to the closest side from the sprayer. As the deposition decreased by increasing the distance from the sprayer, a mean of deposition efficiency of 24%, 32%, 24%, and 14% at distances of 1.5, 2.8, 4.1, and 5.3 m respectively were also recorded (Salyani, 2000b). The low efficiency at the closet distance (1.5 m) might be due to runoff from leaves surfaces. The higher or farther sampling location from the sprayer had the lower deposition and the higher deposition variability (Hoffmann and Salyani, 1996). It looks that discharging distance could affect the deposition, drift, runoff, and the whole deposition efficiency. So adjusting the sprayer configuration to better match the canopy shape and maintain an optimum distance between the sprayer and the target could improve the deposition efficiency (Gu et al., 2012).

2.6 Application Volume

A laboratory and field study by Cunningham and Harden (1998b) showed that increasing spray volume resulted in more deposition on the leaves of citrus; however, the increment was not significant at low volumes. The spray volume of 2000 L/ha was a crucial volume because the retention percent of the leaves decreased as the spray volume increased. Also spraying at a volume rate less than or equal to 2000 L/ha reduced the run-off losses and resulted in the highest spray recovery on tree leaves.

Changing the spray volume affected the copper deposition on the upper side of citrus leaves with no change on the lower side (Whitney et al., 1988). Salyani (1995) found significant differences in the spray deposits on citrus canopies by using different spray volumes; however, the differences varied among different canopy locations. Based on the study outcomes, the spray volume of 2000 L/ha was recommended for Florida citrus application. However, spray penetration and deposition were not affected by spray volume (Salyani and Farooq, 2003). In a study of the effect of abscission chemical on mechanical harvesting efficacy of orange, Koo et al. (1999), found an increase in the deposition as spray volume decreased. Conversely, high spray volumes reduced the force of fruit detachment and increased the percent of removed fruits. Changing the spray volume, did not affect the spray deposition significantly, however, it affected the deposition variability (Coefficient of Variation, CV), significantly (Salyani et al., 1988). In addition, the highest volume (9400 L/ha) gave more deposition uniformity and lower deposition averages than low volume (235 L/ha). Hence, changing the spray volume did not affect the initial mite control, significantly. Similarly, spray volume did not affect the initial value of mortality or residual control of citrus rust mite on fruits.

Hoffmann and Salyani (1996) found a significant negative relationship between spray volume and deposition. They reported that using spray volume rates of 470, 1890, and 4700 L/ha resulted in deposition rates of 1.67, 1.49, and 1.44 mg/cm^2, respectively. The results indicate the advantage of using low spray volumes. In a study of comparing the effects of different volume rates (470, 940, 2350, 4700, and 9400 L/ha) on the deposition on citrus leaves, Salyani and McCoy (1989) found significant increase in the deposition and its variability (CV) by reducing volume rates. The lowest spray volume of

470 L/ha resulted in deposition of 1.37 times as much as the highest volume of 9400 L/ha. The authors related the reduction of the deposition to increasing the runoff rates, which is directly affected by the volume rate. Not only was the deposition on citrus leaves affected by spray volume, but also the interaction of the number of nozzles, disc and core size, and ground speed. At low volume (< 900 L/ha) an increase in the deposition using low number of nozzles and small disc and core size was recorded; however, at high volume (> 2500 L/ha), increasing the number of nozzles and spraying at high speed gave the highest deposition (Salyani, 2000b). Based on these outcomes, the deposition of the spray application on the leaves of citrus trees can be improved by reducing spray volume rates to about 2000 L/ha and improving the spray uniformity by using a different tactic.

2.7 Droplet Size

Deposition on the leaves of citrus trees is directly related to the droplet size (Salyani, 1988, 2000b). Smaller droplet size resulted in the highest on-canopy deposition (Salyani et al., 2009), especially on the close target to the sprayer (Salyani, 1988). However, the smallest droplet size resulted in the lowest deposition efficiency of citrus leaves (Salyani, 1988). Reducing the droplet size increases the drift potential (Salyani and Cromwell, 1992), which could explain the reduction of the deposition efficiency. A laboratory study by Salyani et al. (1987) showed that droplet size of 414 µm gave the highest deposition efficiency (about 95%). However, another laboratory study by Salyani (1988) showed that droplet size of 262.4 µm resulted in the highest efficiency (91.61%). The discrepancy between the droplet sizes of the two studies was returned to an improvement in the droplet size measurements due to modifying the fluid pumping system and the sampling and measuring techniques.

Not only was the deposition efficiency affected by changing droplet size, but also the percent of the coverage area (Salyani et al., 1987) and the runoff losses (Salyani and McCoy, 1989). Then again, Salyani et al. (2009) found no significant differences in drift losses between small and large droplet sizes. In contrast Matthews (2000) reported that it was easy for droplet size of 60-80 µm diameters to be carried out to 46 m in a particular airstream, while only 6-12 m was traveled by a larger droplet size (200-400 µm). Salyani et al. (1987) found that droplet size of 304 µm achieved the highest coverage area.

Big size droplets increase the runoff potential because they tend to meet other droplets and become large and easy to fall down while small size droplets take more time to be large enough to fall down. As deposited materials are expected to be washed by rain or degraded by sun light, Salyani (2003) studied the effects of different droplet sizes on rain wash-off and solar degradation. He found a significant increase in the rain wash-off as the droplet size decreased. In contrast, significantly higher degradation occurred with the largest droplet size. Therefore, the droplet size plays a crucial role in determining the deposition efficiency and reducing spray materials losses.

Droplet size directly affected the droplet speed and trajectory (Bagherpour et al., 2012). At a distance of 0.5 m from the nozzle exit of different nozzle types, larger droplet sizes (> 400 µm) were faster (4.5 − 8.5 m/s) than smaller ones (< 400 µm) of 0.5 − 2.0 m/s (Nuyttens et al., 2007).

2.8 Sprayer Type

Chemical materials can be applied directly onto the tree canopy. However, these materials might not be able to reach the top of the tree canopy and always deposit on the target side that is facing the sprayer outlet. Therefore, orchard sprayers are equipped with air-discharging systems to transport the spray droplets to the tree canopy and help them to penetrate within it. The total deposition on both sides of the leaves was significantly increased by using air-jet as compared with no air-jet assistance (Khdair et al., 1994). Sprayers could be differentiated based on their air systems. The air system could have axial-flow, cross-flow, or centrifugal fans. However, the sprayer could be a low-profile outlet, air-tower outlet, or tunnel sprayer based on the air-system outlet.

2.9 Axial-Flow Fans

Sprayers equipped with axial-flow fans are designed based on the Daugherty's design, in which, the fan delivers the air jet parallel to its axis, then the air turns 90° to exit the fan housing through radial slot outlets (Fox et al., 2008). Axial-flow fan sprayers are widely used in orchard applications. They have very good ability to discharge large air volume rates at higher efficiencies as compared with other types (Bleier, 1998). In addition, their maintenance is easier.

During the sprayer operation, the axial-flow fan generates upward and downward streams on both sides of the sprayer in relation to the fan-rotation direction. Therefore, the sprayer will deliver asymmetrical airflow on both sides (Landers and Gil, 2006). At the same time, the delivered air might have different velocities based on how close the measuring is from the fan wheel. Salyani and Hoffmann (1996) recorded a lack of uniformity in the air velocity across and along the sprayer's fan outlet. Lower air velocities were recorded at the outlet side close to the fan wheel and at the lower halves of the outlet as compared with the conical-air-deflector side and the upper halves, respectively.

To overcome this issue, different designs of air system were made. For example, Landers and Gil (2006) modified the air deflector of an axial-flow fan that delivers the air through radial slots on the fan house circumference by extending its outlet height to direct the airflow relatively horizontal toward the canopy. This modification improved the symmetry of the air stream on both sides to reach 90% and kept the plume within the height of the canopy (about 2 m). Their results also showed an improvement of 25% in the overall deposition within the grape tree canopy as compared with the conventional design.

Most of the axial-flow sprayers have one fan, only; however, some of them might have two axial-flow fans or more. Installing two axial-flow fans on the same sprayer was done to overcome the issue of the asymmetric air stream on both sides of the sprayer. The two fans turn in reverse rotation to balance the asymmetric airflow of each other. Garcia-Ramos et al. (2009) tested the sprayer of two axial-flow fans with only one fan activated and both fans. Their results showed that activating both fans, simultaneously, increased the deposition and its variability as compared with one fan active, only.

Discharging airflow rates and spray volumes according to the foliage density is an ultimate goal. For an air-system having one fan, only, adjusting the air-volume rates of the fan will affect the delivered air on both sides, simultaneously. Most of the time, trees on both sides of the sprayer are not similar in their sizes and densities; therefore, differentiating the airflow between the two sides might be necessary. Pai et al. (2008) modified the sprayer air system to adjust the airflow of one side based on the characteristics of the tree canopy. They installed an electrically adjusted plate on the air-blast sprayer and tested its ability to adjust airflow rates based on the tree foliage density. Moving the deflector plate from its innermost to outermost position resulted in changing the horizontal airflow rate from 7.6 to 1.9 m^3/sec, respectively. Changing the airflow rates differentiated the penetration of the air across tree canopies of different foliage densities. It gave 37% reduction in the off-target deposition average at high application rate. Using the same system on both sides of the sprayer could improve the deposition efficiency; however, having a reduced airflow at both sides will lead to have a bypass for the other flow as the sprayer’s fan generates a fixed airflow rate at fixed speed.

2.10 Cross-Flow Fans

Cross-flow fans discharge the air across their axis. They are small and consequently have small air volume rates as compared to the axial-flow fans. Therefore, air-assisted sprayers with cross-flow fans use two fans or more on each side. When it comes to the variation in the air volume rates between both sides of the sprayer, cross-flow fans can be adjusted to achieve that goal, easily because most of the cross-flow fans are operated by a hydraulic motor, which make it easy to change the speed of each fan, independently. Cross-flow fans generally are arranged vertically on top of each other along their axis.

2.10.1 **Low-Profile Outlets**

This technique is always used with axial-flow fan sprayers, where the air exits the fan house into the tree canopy radially along the fan house perimeter. Delivered air transfers the spray materials from near the ground to the tree canopy along its height. Moving the airflow for long distance to bridge the gap between the low profile sprayer and the top of the tree canopy was insufficient in some cases. Low-profile sprayers significantly decreased the deposition on the leaves as the height increased

(Cunningham and Harden, 1998a). In contrast, Derksen and Gray (1995) found that increasing the delivered spray of the FMC (Food Machinery Corporation) sprayer resulted in greater deposition on the top level of the canopy. However, the top nozzles of the FMC sprayer were lower than that of the Friend Air Kadet II sprayer. For that concern of the long distance that should be moved by the airflow before reaching the top of the tree canopy, the air outlets of the sprayer are extended to be closed to the treetops.

2.10.2 **Air-Tower Outlets**

Air-tower sprayers use a vertical outlet to apply the spray material almost horizontally toward the canopy. This requires the air-tower to be as long as the tree height or at least as half the tree height. Most of the time, two cross-flow fans or more are built on top of each other to form the required height of the tower; however, in some cases, air-tower outlets on both sides of the sprayer can be used with a single axial-flow fan. The sprayer that delivers the spray horizontally along the tree height resulted in a more uniform deposition at the bottom, middle, and top zones of the tree canopy than the low-profile sprayer (Cunningham and Harden, 1998a). Using the tower-sprayer reduced the runoff recorded the lowest drift above the tree zone as compared with low-profile sprayers. Landers and Gil (2006) found that modifying the air deflector to direct the airflow relatively horizontal toward the canopy improved the symmetry to 90% and kept the plume within the height of the canopy (2 m). Derksen et al. (2004) compared between an air-tower sprayer equipped with cross-flow fans and a conventional orchard sprayer equipped with an axial-flow fan and found more uniform deposition along the canopy height from using the air-tower sprayer. However, it has a lower mean deposition than the conventional sprayer. Fox et al. (2008) recommended using the air-tower sprayer because it reduces the droplets traveling time to reach the target. Calibrating the air volume of these sprayers and its velocity to match the canopy size and density could minimize the spray drift. When it comes to the delivered-air velocity of a sprayer with two cross-flow fans, Fox et al. (1992) tested the effect of inclining the top fan on the air velocity at different distances from the sprayer outlet. They found that inclining the upper fan at 20°, for both fan speeds, the air jet velocity at 3 m from the outlet slightly increased; however, it decreased beyond 4.6 m as compared with both fans vertical. These outcomes may leads to reduce the drift beyond the tree canopy.

2.10.3 **Tunnel Sprayer**

A considerable spray drift is associated with the use of the low profile and air-tower sprayers. For measuring the drift of an air-blast sprayer, Salyani (1995) found that the ground and airborne drift has reached a distance up to 195 m far away from the sprayer outlet. Salyani and Cromwell (1992), in their comparisons between aerial (both fixed-wings and rotary-wings) aircrafts and ground (low and high volume air-blast) sprayers, found that low-volume ground equipment resulted in the highest airborne drift. To overcome the spray drift problem and increase the spray efficiency, Peterson and Hogmire (1994) designed and tested a tunnel sprayer. The tunnel sprayer goes over the whole tree canopy in one pass and applies spray to the tree canopy from two sides using four cross-flow fans. Using the tunnel sprayer improved the spray deposition and reduced the drift as compared with other sprayer types. However, its use was limited to dwarf trees because its maximum inside height and width are 3.0 m.

CHAPTER 3
WIND VARIABILITY IN CITRUS SPRAY APPLICATIONS

In citrus application, air-assisted sprayers use an air-jet to transport the spray droplets to the canopy and help them penetrate within it. Ambient wind could affect the movement of the air-jet and hence, its potential to transport the droplets (Khdair et al., 1994). Spray could be postponed if wind speed is high (greater than 4.5 m/s); however, it cannot be canceled. Until now, pesticide application is still the most effective way of controlling pests and diseases. In field conditions, the wind is always there and cannot be avoided, completely.

Wind could reduce the air-jet velocity or shift its direction (Fox et al., 1985). Wind velocity is the most influential factor on drift (Bird et al., 1996; Fritz, 2006). It directly affects the traveling distance of drifted droplets. Wind direction was also found to be a significant factor affecting the spray efficiency (Thistle et al., 1998; Salyani, 2000b). Strong winds could move the droplets out of the application site or redirect them onto very sensitive areas or objects. Wind also could move the spray droplets beyond the second or third tree row downwind (Spray Drift Task Force, 1997). In this case, deposition distribution between the two sides of the sprayer will be different. In general, the more uniform pesticide coverage on targets is, the more efficient pest control will be. However, any distortion of the sprayer air-jet may result in non-uniform spray deposition and hence, poor biological efficacy.

Wind conditions within a grove usually differ from those outside the grove to some extent. These differences are more evident within the canopy height. A comparison of 10-year wind conditions recorded inside and outside groves showed a significant reduction in the wind velocity within the canopy height inside the groves as compared with the outside measurements (Renaud et al., 2010).

In spray application, it is essential to know the average wind velocity for a specific time in order to schedule the application. However, it is also important to know the variability associated with that average because changes in the wind velocity could affect the spray uniformity within the grove. In general, weather conditions are given as averages for some periods of interest. For example, Florida Automated Weather Network (FAWN) reports wind conditions based on a 15-min interval. However, the data may vary substantially within the reporting period. In field spray treatments, sprayer applications face such variations in wind conditions, which might become inconspicuous by the data averaging. Such momentary variability in wind conditions may change the spray uniformity to some extent.

Weather conditions usually are measured at about 2- and 10-m heights (ASABE Standards, 2009) outside the grove. Studying these conditions at different levels within the canopy height might help the applicator to understand deposition variability on the canopy. Such information could be useful in improving spray efficiency in grove applications.

Thus, it is important to know to what extent weather conditions recorded outside groves can reflect the conditions within the grove. It is also useful to know the wind variability associated with different averaging intervals. Specific objectives of this study were to:

1. Determine the relationship between weather conditions collected outside and within a citrus grove.
2. Find the variability associated with wind velocity and direction at different measuring heights within citrus canopies at different reporting intervals.

3.1 Materials and Methods

3.1.1 Data Collection

A weather station (Figure 3-1) was set up inside a citrus grove in Lake Alfred, Florida (N 28° 06' 18.93", W 81° 42' 56.36"). It was installed at the location of a missing tree (within a tree row). The rows were set in East-West direction. The average tree height was about 4 m and the tree spacing was 4 × 6 m within and between the rows, respectively. Tree canopies were skirted about 0.3 to 0.5 m above ground.

The weather station (Campbell Scientific, Logan, UT) consisted of a data logger (CR10X) and two sets of cup anemometer and vane direction sensors (03001 Wind Sentry Anemometer/Vane) to measure wind velocity and direction at two heights. The accuracy/ threshold wind velocities (a minimum wind velocity required to rotate the sensor) for the anemometers were ±0.5/0.5 m/s, and for the vanes were ±5°/0.8 m/s, respectively (Campbell Scientific, 2007). The specified thresholds are for starting the cup rotation but during the rotation, they can be as low as 0.2 m/s. The upper height was fixed at 10 m above the ground for all measurements (ASABE Standards, 2009). The 10-m height was chosen to be comparable with the FAWN measuring height. The lower height varied and its sensors were installed at 3.6, 3.0, 2.4, 1.8, 1.2, and 0.6 m for measurement pairs. These heights (located in the missing tree space) were within the canopy level and hence, more relevant to the spray droplet movement.

Upper wind velocity and direction sensors were 0.5 m apart atop the station pole, while the lower sensors were 1.5 m apart (with the pole running in the middle) to minimize wind shield effect of the pole (Leahey et al., 1989). The instrumentation included dry bulb temperature sensors at both heights and a wet bulb temperature sensor fixed at 2.5 m height.

Figure 3-1 The weather station set up within a citrus grove (Photo courtesy of author, Ahmed Al-Jumaili).

For each height, the data were recorded continuously at 1-s interval for at least 7 days between 18 February and 5 May 2011. The data were transferred to a laptop computer at 24 h cycle for further processing. Matching data from the FAWN (station No. 330, Lake Alfred, Florida) were also recorded for the same period. After completing the data collection in the grove, the weather station was relocated to 7 m north of the FAWN station to collect data from the two neighboring stations for the same period. The sensors of two stations had the same height. The FAWN used a sonar (ultrasonic) sensor while the other station was equipped with the cup anemometer. The ultrasonic sensor (model 425A, Vaisala, Helsinki, Finland) had an accuracy of ±0.14 m/s and ±2° for wind velocity and direction. It has almost zero wind velocity threshold. Wind speed and direction were collected on both stations at the same height (10 m) for seven days, simultaneously. A regression analysis between wind speeds recorded by the two stations was used to establish a relationship between the readings of the two sensors. The established relationship (regression equation) was used to adjust the readouts of the GROVE station sensor, recorded in the grove at 10 m height. The same procedure was done to the wind direction sensors.

3.1.2 **Data Analysis**

Wind velocity readings were processed as scalar quantities (El-Fouly et al., 2008) while vector analysis was applied to the wind direction data. For a comparison between the data recorded outside and within the grove, data collected in the grove were averaged based on a 15-min interval to match FAWN reporting interval. Each day was divided into daytime (8:00 am to 6:00 pm), nighttime (8:00 pm to 6:00 am), and transition time for the rest of the day (Bird et al., 1996). These categories were used to identify if there is a difference in weather conditions between day and night times.

Sample mean, standard deviation (SD), coefficient of variation (CV), maximum value (Max), minimum value (Min), and range were used to identify wind variability and make comparisons among the study variables. Wind direction values were grouped into eight half quadrants: north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W), and northwest (NW). Wind conditions recorded outside the grove and those recorded within the grove are mentioned as FAWN and GROVE, respectively. Differences between wind directions recorded by the FAWN and GROVE stations at 10 m height were calculated as described in Mori (1986). However, the method was modified to show both difference signs (positive or negative). A correlation analysis was used to identify the relationship between different datasets recorded at the two stations or at two different heights (within the grove). The standard deviation of the wind direction means was calculated through the Equation 3-1 (Mori, 1986).

$$SD = (2Ln(R))^{0.5} \tag{3-1}$$

where:

$$R = (Sa^2 + Ca^2)^{0.5}$$

$$Sa=n^{1}\sum \sin D_i$$

$$Sa=n^{1}\sum \cos D_i$$

D_i = i^{th} angle of wind direction

Using the collected 1-s interval data, pairs of maximum wind velocities at 10 m height and at each lower height (3.6, 3.0, 2.4, 1.8, 1.2, or 0.6 m) were calculated for 15- and 60-min intervals, separately. For comparison among different reporting intervals, wind velocity data recorded at 1-s interval within the grove at 10 m height for one hour, was chosen randomly and averaged based on 1- and 15-min intervals. A simple regression analysis was used to relate the averages of wind velocity or direction that were recorded by the two stations or those recorded within the grove at different heights. In addition, the ratio between the two maximum wind velocities (wind velocity at lower height/ wind velocity at 10-m height) was used to express the relationship between the two measurements.

Since about 24% of data recorded at the 10-m height were less than 1.5 m/s and their corresponding data at lower heights were nearly zero, they were excluded from further analysis. These low wind velocities averaged 0.81 and 0.09 m/s at the 10-m and lower heights, respectively. Practically, these low velocities could not have a significant effect on the sprayer air-jet deflection (Endalew et al., 2010) and hence, spray deposition. However, including them in the comparison could skew the trend estimates. Therefore, the minimum velocity of 1.5 m/s was used as a cutoff point to have comparable matching data for all height pairs. Data averaging and adjusting was done using Matlab® software, R2010b (The Mathworks, Inc., Natick, Mass.); however, the variance was analyzed using SAS® software, 9.2 (SAS Institute, Inc., Cary, N.C.). Means of wind velocity and direction recorded by the two stations were compared using t-test at 5% level of significance.

3.2 Results and Discussion

3.2.1 GROVE Wind Data Correction

Figure 3-2 shows the comparative 15-min interval wind velocity and direction data recorded by the GROVE and FAWN stations, when they were used next to each other for one day. Wind velocity trends on both stations were in good agreement; however, their averages were 1.67 and 2.15 m/s, respectively. For the 7-day recording period, the averages were 1.21 and 1.52 m/s for the GROVE and FAWN stations, respectively. Wind directions of the two stations showed similar trends in windy conditions but the trends did not match when no wind velocity was recorded by the GROVE (cup) anemometer. This could be associated with the threshold and accuracy of the sensor measurements.

Thus, due to the very good agreement with the FAWN readings in windy conditions, wind direction values recorded in the grove were used as collected (without any correction). However, wind velocity recorded in the grove (at 10-m height) was corrected in order to be comparable with FAWN readings, using the following relationship.

$$y = 0.95\,x + 0.33 \qquad R^2 = 0.96, \quad N = 504 \tag{3-2}$$

Where, y and x are the GROVE corrected and measured wind velocities (m/s), respectively.

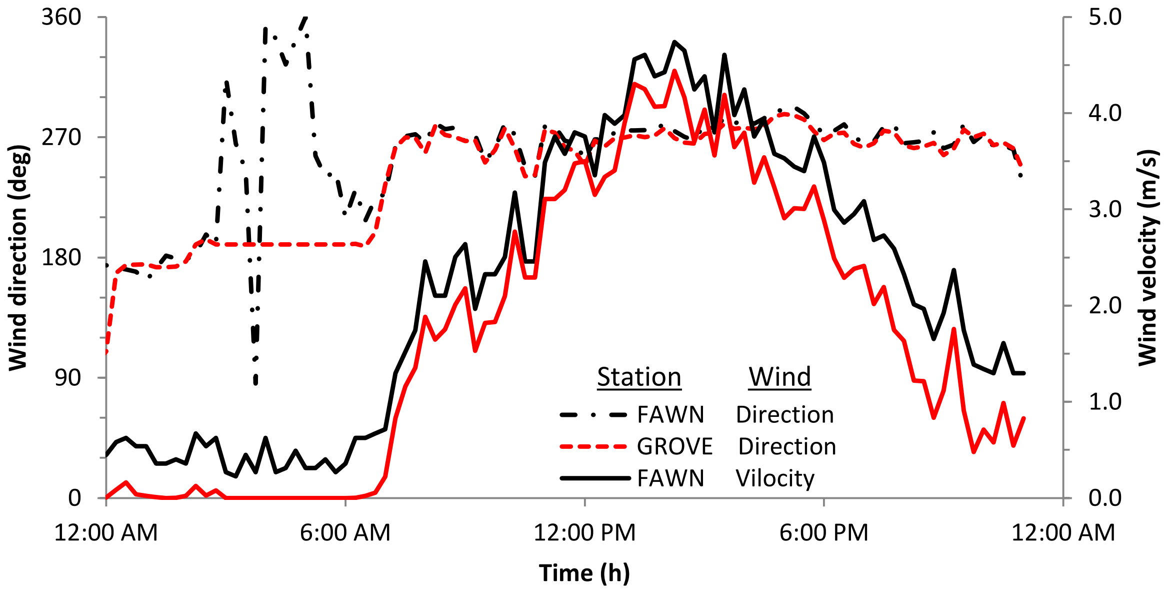

Figure 3-2. Comparison between wind velocity (solid lines) and direction (dotted lines) recorded by the FAWN and GROVE stations at 10-m height (15-min interval).

3.2.2 **GROVE and FAWN Comparison**

3.2.2.1 Wind velocity

Figure 3-3 shows the relationship between the GROVE and FAWN wind velocities (15-min interval), recorded at 10-m height. The correlation coefficient (r) between them was 0.69 (R^2 = 0.48). Averaged over the 6-week comparison period, the respective wind velocities were 2.33 and 1.98 m/s. The two averages were significantly different. The difference may be explained by the presence of buildings (about 10-m height at 50 m to the north from the FAWN site) and trees (about 15 m tall oak trees at 10 m to the south), which could have reduced the wind velocity to some extent. Thus, the use of FAWN weather data to characterize the weather condition inside a grove with conditions similar to those described in this study may be objectionable.

The wind variability between the GROVE and FAWN might be related to the distance between the stations and the difference in their surrounding features. The stations were about 580 m apart and hence, wind recorded by one station at a given moment may not necessarily be the same wind at the other station. In addition, wind sensors at the two stations were different. These sensors could respond to the same wind differently, especially at low velocities. For instance, the cup anemometer has a static friction and inertia effect while the ultrasonic sensor does not have that limitation. The moving parts of the cup anemometer make it less sensitive to low wind velocities (Fons, 1940). In a comparison study between cup and ultrasonic anemometers, Yahaya and Frangi (2003) found about 6% increase in the wind velocity averages recorded by the ultrasonic sensor as compared with cup anemometer readings. Another comparison between GROVE and FAWN was done by using maximum wind velocity. Based on 15-min average, GROVE wind velocity reached a maximum of 9.77 m/s at 4:00 pm on someday; similarly, FAWN station recorded the highest wind velocity average (8.54 m/s) at the same time of the same day. This indicates that wind velocity recorded at one station, shortly, was not necessarily the same at the other station; however, general trends of wind velocities on both locations were comparable.

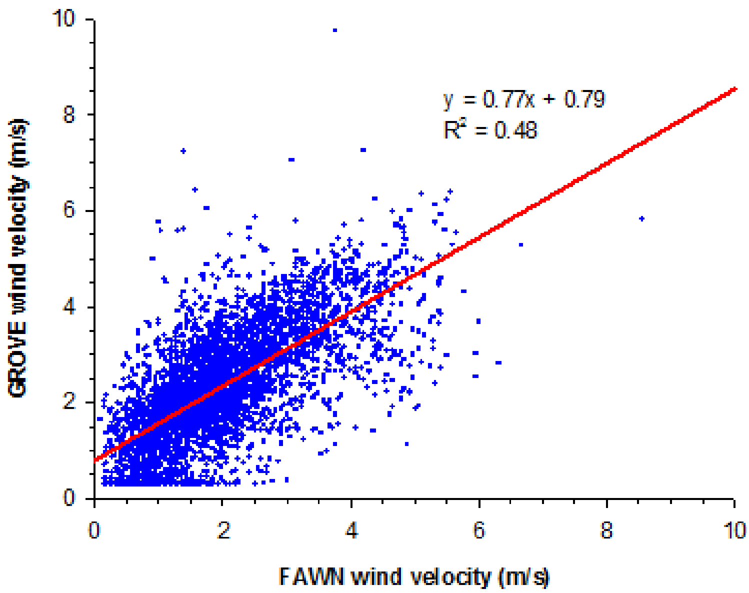

Figure 3-3. Relationship between GROVE and FAWN wind velocities.

3.2.2.2 Wind direction

Over six weeks of 15-min interval measurements, results of the regression analysis showed that GROVE wind direction was significantly correlated with FAWN wind direction (r = 0.94). Wind direction averaged 161° and 166° at the GROVE and FAWN stations, respectively. Based on a t-test, the averages were significantly different. The difference might be related to setting the default north of the sensor at each station, specifications for sensors, and the random error of the measurements. A regression analysis of the two directions resulted in R^2 = 0.88, which indicates a good agreement between the readings on the two locations. The results agreed with results found by Baynton et al. (1965).

Figure 3-4 shows the frequencies of having wind directions in each half quadrant (45°) for the GROVE and FAWN measurements. Wind directions on both locations agreed most of the time. The figure indicates that the winds came mostly from the east.

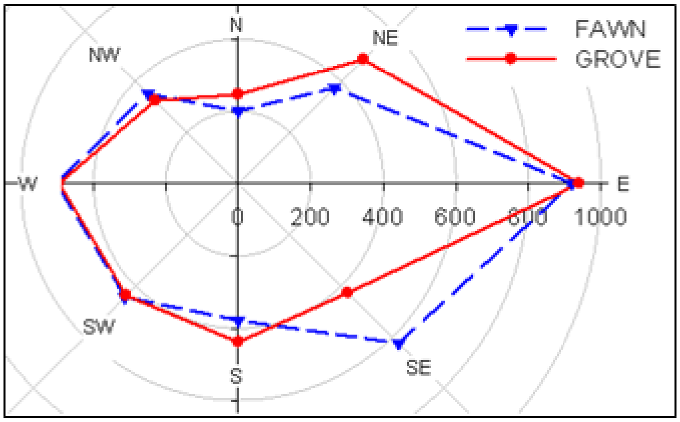

Figure 3-4. Relationship between GROVE and FAWN wind direction. The circles show the frequency of the measurements.

Table 3-1 shows the difference in wind direction recorded by the two stations at eight half quadrants. The results indicate no effect of wind direction on the difference between the readings of the two stations.

Table 3-1. Absolute values of the differences in wind direction measured by the GROVE and FAWN stations.

Wind Direction	No.	Mean (°)	SD (°)	CV (%)
N	158	27	34	126
NE	395	24	24	103
E	919	18	22	124
SE	626	25	26	101
S	385	23	28	121
SW	456	23	23	100
W	504	18	25	139
NW	352	25	36	145

3.2.2.3 Wind velocity difference versus direction

In order to test if wind direction influences wind velocity at GROVE and FAWN, velocity differences between the two locations were grouped within eight half quadrants

(Table 3-2). These differences were not highly correlated (r = −0.20) with FAWN wind direction. However, directions of S and SW gave the highest differences, −1.06 and −0.77 m/s, respectively. The negative sign means that GROVE wind velocity was higher than FAWN wind velocity. Based on the physical location of each weather station, the FAWN station was located about 10 m to the north of a row of tall (about 15 m) oak trees. These trees were taller than the height of the wind sensors. Thus, it could restrict winds coming from south as explained by Lee et al. (2010). In contrast, the sensors of the GROVE station were above the canopy height.

Table 3-2. Wind velocity differences (m/s) between GROVE and FAWN in relation to the wind direction.

Wind Direction	No.	Mean (m/s)	SD (m/s)	CV (%)
N	190	-0.18	0.73	406
NE	421	0.10	0.74	721
E	945	-0.07	0.80	1212
SE	655	-0.32	0.93	292
S	404	-1.06	0.96	90
SW	464	-0.77	0.85	110
W	530	-0.38	0.95	250
NW	384	-0.35	0.70	202

Overall, the trends and values of the wind velocity and direction recorded at GROVE station were comparable to those recorded at FAWN station. Thus, wind direction recorded by the latter (outside the grove) may be used to represent the prevailing wind direction inside the grove even though there could be some variability in individual (momentary) readings.

3.2.3 **Within the GROVE Comparisons**

Figure 3-5 shows the variability of wind velocity and direction within a minute, chosen randomly from all collected data. The measurements were recorded at 10.0 and 3.0 m heights at 1-s interval. Within that short time period, wind velocity and direction at

3.0 m height (canopy level) changed (maximum – minimum) about 6.0 m/s and 74°, respectively. They showed a high variability (CV = 46% and 43% for wind velocity and direction, respectively). The changes in the wind velocity at both heights have a similar general trend even though wind velocity at the lower height averaged 2.34 m/s less than the one measured at the upper height. Wind directions on the two heights were not in good agreement. These wind direction changes are in line with the variability reported by Baynton et al. (1965). They found no clear trend in the wind direction changes within the canopy height. The changes in wind condition might happen anytime; therefore, such variations could have significant influence on the movement of the sprayer air-jet, droplet movement, and spray deposition.

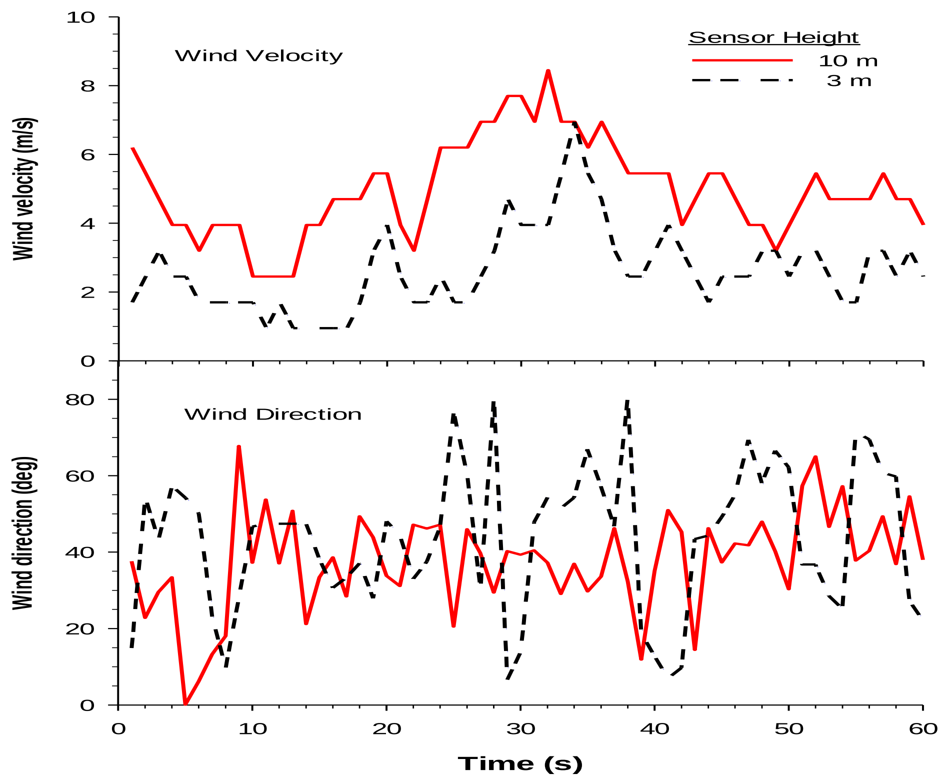

Figure 3-5. Typical trends of wind velocity (top) and direction (bottom) for a 1-min recording period.

3.2.3.1 Measurement height effect

Figure 3-6 shows the relationship between the wind velocities (top) and directions (bottom) recorded at 3.6 and 10 m heights, averaged hourly. The velocities were significantly correlated (r = 0.93) and their respective means of 0.63 and 2.11 m/s were significantly different. Wind velocity has similar trends at both heights. However, it reduced significantly near or within the tree canopy level. The results agreed with Renaud et al. (2010). Both velocities averaged higher during daytime (0.90 and 2.61 m/s) than at nighttime (0.34 and 1.56 m/s), respectively. In addition, the ratio of wind velocity at 3.6 m to the velocity at 10 m height was 0.34, 0.22, and 0.30 at daytime, nighttime, and transition time (day to night and vice versa), respectively. The reduction in the wind velocity at night gives a favorable condition for spray application (Hoffmann and Salyani, 1996).

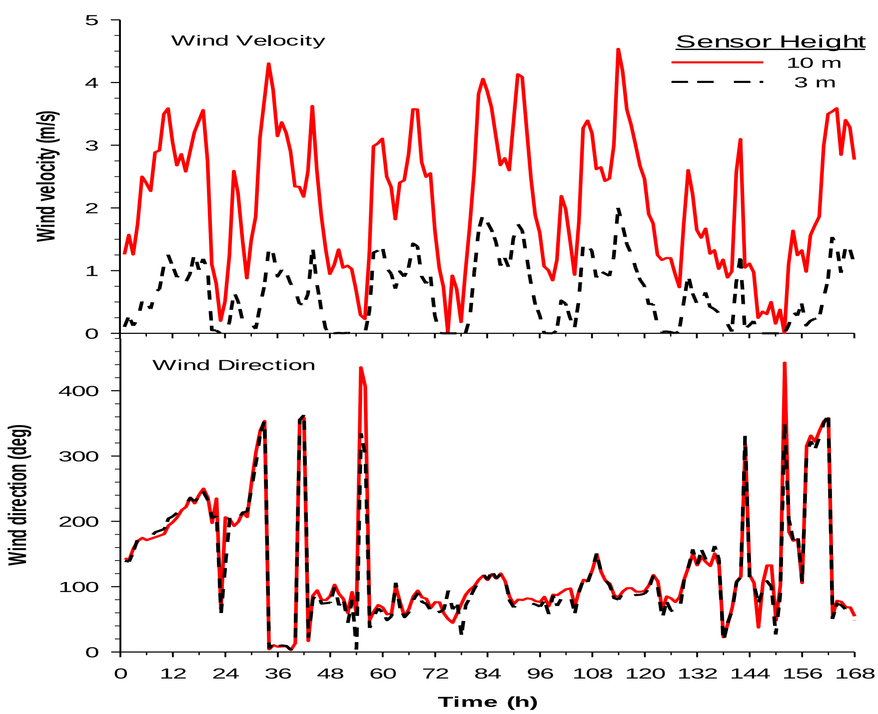

Figure 3-6. Relationship between wind velocities (top) and directions (bottom) recorded at the 10.0 and 3.6 m heights.

In contrast to the wind velocity, wind directions recorded at the lower height were in good agreement and highly correlated (r = 0.98) with those recorded at the upper height. Some wind direction points are more than 360°. The increase came from adding 360° to small angles (slightly larger than zero) to be comparable with their corresponding directions that were a little lower than 360°.

Differences between wind velocities recorded at 3.6 and 10 m heights had no correlation (r = 0.003) with wind direction; however, the differences were higher (average of 1.95 m/s) when the winds were coming from the north direction. This might be related to the tree-row direction (East-West).

Averaging wind velocity over time may put the velocity within an acceptable range for spray application; however, accounting for the wind velocity peaks might be more relevant to spray applications (Thomas F. Burks, personal communication, University of Florida, 2011;(Koch et al., 2005). Maximum wind velocities within each hour, recorded at 10.0 and 3.6 m heights, were compared for one day (Figure 3-7).

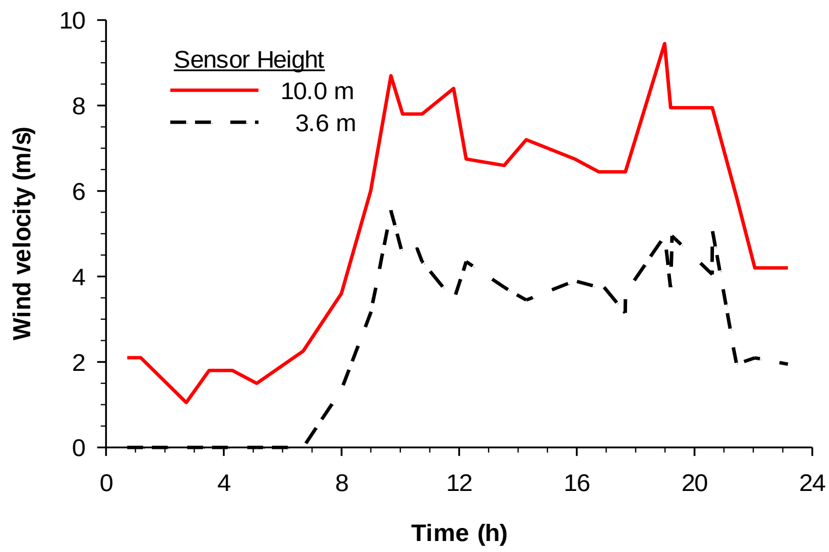

Figure 3-7. Maximum wind velocities at the 10.0 and 3.6 m heights.

Results showed that the maximums of wind velocity recorded at 3.6 m generally followed the trend of the maximums of wind velocity recorded at the 10-m height. However, the overall average of maximums (2.07 m/s) of the 3.6-m height was less than that of the 10-m height (4.63 m/s). Within that day, maximum velocities at the respective heights changed in ranges of 0 – 5.6 and 1.1 – 9.5 m/s with CVs of 97% and 58%, respectively. The maximum wind velocity of about 2.0 m/s or less recorded at 10 m height resulted in almost zero velocity at the lower height. Similar results were obtained for other paired heights.

3.2.3.2 Comparison of recording intervals

Figure 3-8 shows wind velocity at 10 m height recorded at 1-s interval during one hour. These data were also averaged based on 1- and 15-min intervals. It is visually clear that the wind velocity was very variable at small intervals. The velocity at 1-s interval changed within a range of 0.75 to 9.0 m/s (CV=31%). However, averaging the same data based on 15-min interval, which is the same interval used by the FAWN, reduced the velocity range to 4.2 to 4.4 m/s (CV of 3%).

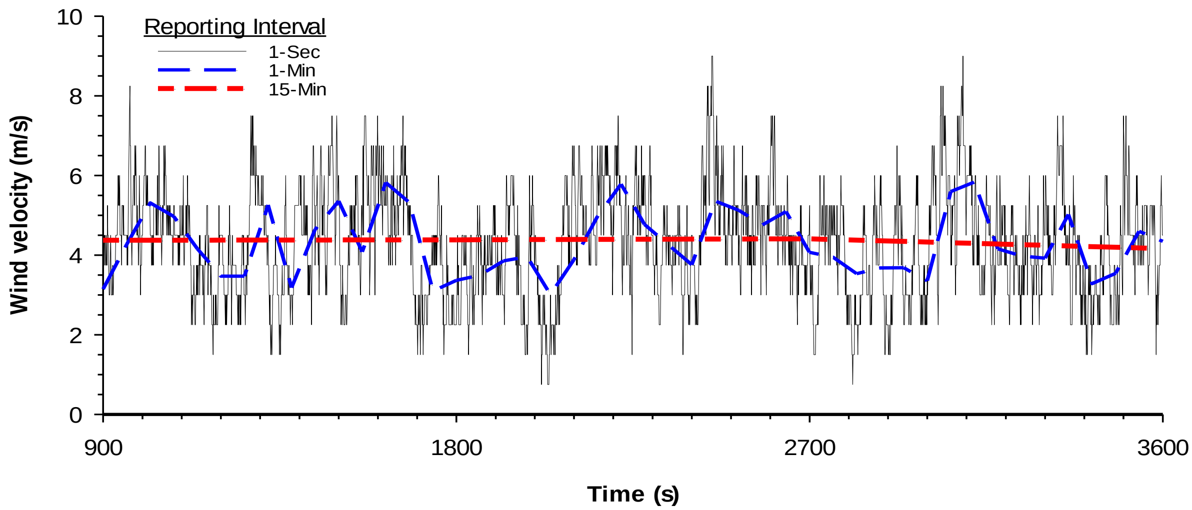

Figure 3-8. Variability of wind velocity at different measuring intervals.

Although the sample mean remained the same for all different intervals, measures of spread (Range, SD, and CV) of the sample reduced sharply by increasing the averaging interval. For instance, changing the averaging interval from 1-s to 15-min reduced the CV by about 90%. These results revealed that the reporting of wind conditions at longer intervals would not reflect the actual effect of wind for spray applications.

3.2.4 **Prediction of Wind Velocity**

3.2.4.1 Above the canopy height

Comparison of the wind velocity obtained by the FAWN and GROVE stations resulted in the following regression equation:

$$wv_G = 0.77 \times wv_F + 0.79 \tag{3-3}$$

Where, wv_G and wv_F are the GROVE and FAWN wind velocities (m/s) recorded at 10 m height, respectively.

Equation 3-3 utilizes wind velocity recorded at 10 m height outside groves to estimate wind velocity above the canopy. The low coefficient of determination (R^2= 0.48) indicates high variability associated with wind velocity measurements. Note that, including wind direction in the analysis (multiple-regression) did not improve the estimation of the wind velocity to any great extent. Thus, wind direction was not included in the prediction equation.

3.2.4.2 Within the canopy height

Figure 3-9 shows established relationships of the acceptable data (> 1.5 m/s) for each height. Due to the high number of data points within one chart, the points were not displayed around the fitting lines. The figure shows that wind velocities recorded at lower heights were considerably less than those measured at the 10-m height. They also diminish gradually as the measurement is taken nearer to the ground level. The crossing of the 1.2-m and 0.6-m regression lines could be attributed to the open area underneath the canopy (canopies were not touching the ground). Overall, these results agree with those reported in Fons (1940).

In spray applications, higher wind velocities could have more impact on deposition than lower velocities. Using the wind velocity averages, which include the lower velocities, may not be a reasonable approach in explaining a wind-related variability in the deposition. Instead, using maximum wind velocities recorded at different heights might be more appropriate in interpreting wind effects.

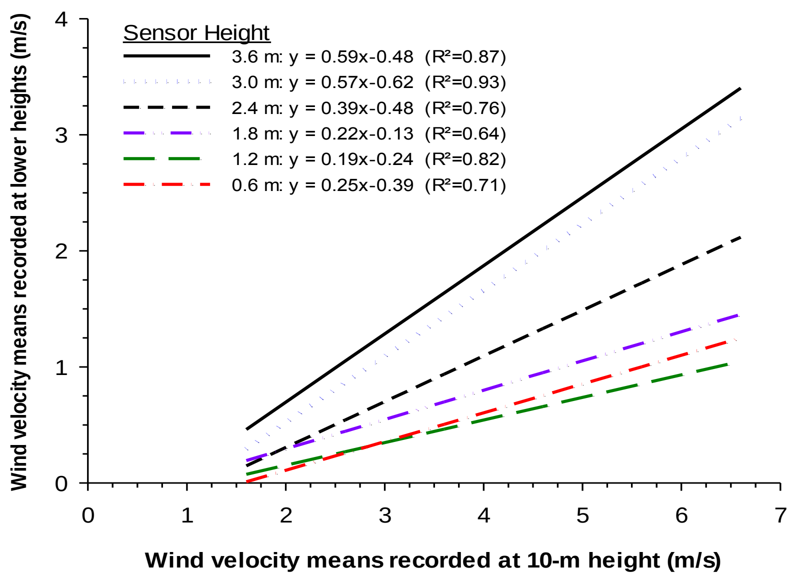

Figure 3-9. Relationships between wind velocity averages recorded at different heights within the grove at 15-min interval.

Figure 3-10 shows the relationship between maximum wind velocities recorded at the upper height (10 m) and those recorded at lower heights (3.6, 3.0, 2.4, 1.8, 1.2, and 0.6 m). Each line represents a linear fitting model for wind velocity data for each pair. Since comparisons were made at different times, wind velocity ranges were different. Results revealed that increasing wind velocity at 10-m height results in a corresponding increase in the velocity recorded at each lower height. The higher the sensor location the greater the wind velocity. Measurements within the lowest quarter of the canopy height (about 1.0 m) were very similar in their maximums; however, the differences were more pronounced within higher quarters. This observation reveals that the effect of wind on deposition could be more evident within the top parts of the canopy than the lower canopy levels. The reduction in the wind velocity is clearly related to the presence of the canopy at the measurement height as reported by Lee et al. (2010).

The averages of the wind velocity ratios (lower height/ 10-m height readings) were 0.59, 0.55, 0.36, 0.30, 0.24, and 0.20 for the heights of 3.6, 3.0, 2.4, 1.8, 1.2, and 0.6 m, respectively. The ratios decreased at the lower measurement levels. The results agreed with Baynton et al. (1965). However, the magnitudes were different due to the differences in the canopy characteristics. The ratio between the measurements at the 3.6- and 10-m was not comparable to the one obtained in an open area. These ratios were 59 and 82% for within the grove and open-area measurements, respectively.

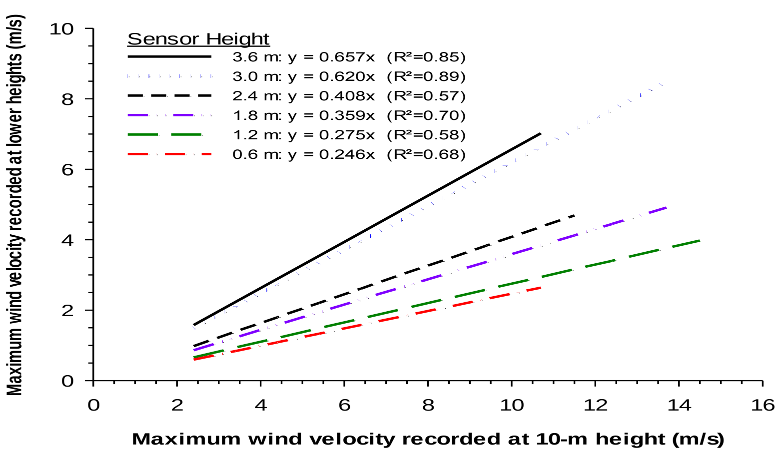

Figure 3-10. Relationships between wind velocity maximums at different heights.

3.2.4.3 Wind velocity ratios

Figure 3-11 shows the ratios (lower/upper height readings) of maximum wind velocities at different heights within the canopy. This information could be useful in predicting the wind velocity within a grove based on the measurements taken above the canopy level (10-m height). At the same windy condition, different wind velocities were recorded at different measuring height within the canopy height. The results indicate very low wind velocities when measurements were made close to the ground level. Thus, the concern about the wind effect on deposition should be focused on the upper parts of the tree canopy.

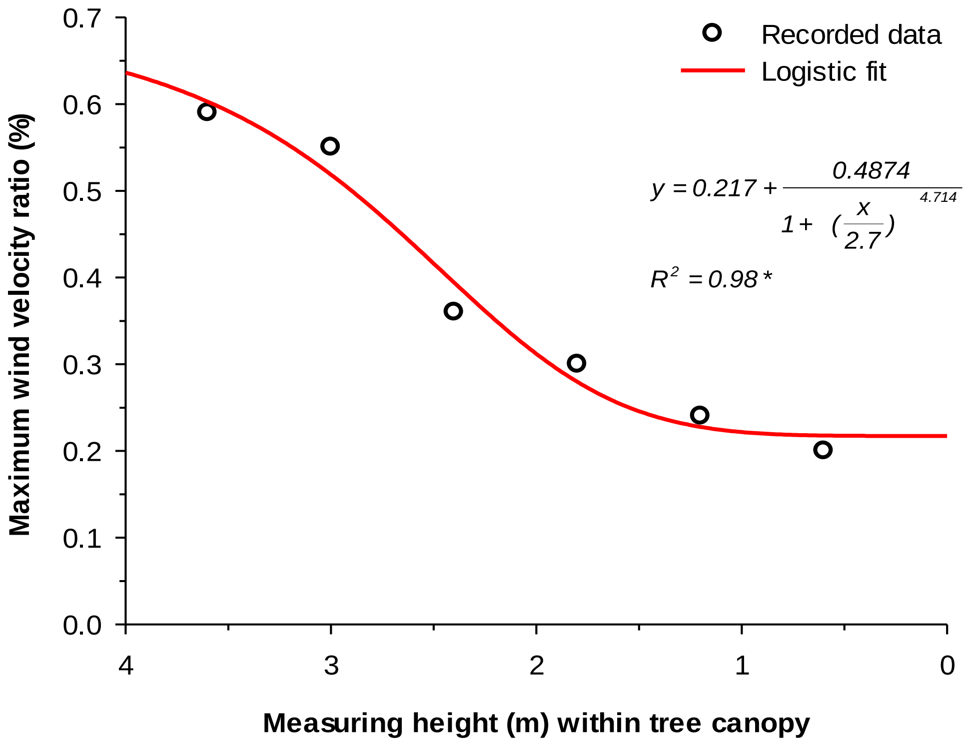

Figure 3-11. The change in maximum wind velocity ratio within the canopy height.*= significant at 5% level.

Based on the wind conditions observed in this study, the following conclusions could be drawn.

1. For field characteristics similar to those described in this study, wind velocity and direction measured at 10 m height and about 550 m beyond the citrus grove did not reliably represent the wind condition recorded within the grove.

2. Averaging wind speed or taking the maximums showed the similar trends of variability at different measuring heights.

3. The tree canopies significantly reduced wind velocity, but the reduction depended on the measurement height. The reduction reached 40% at about 0.5 m below the canopy height (4 m). However, it could reach 90% at the lower height of the canopy (0.6 m).

4. Wind velocity at the canopy level could be estimated from the measurements made at 10 m height inside the grove. However, wind condition within citrus groves varies substantially even within a few seconds. Wind gusts could reach 5 m/s or higher but these gusts may be masked by averaging wind speed. Such variability could affect spray deposition substantially.

CHAPTER 4
DISTORTION OF SIMULATED AIR-JET OF AIR-ASSISTED SPRAYER AND CHANGES IN ITS DEPOSITION DUE TO THE AMBIENT WIND

In any air-assisted spray application, the ability of the air-jet to transport the spray droplets to the canopy and obtain a uniform coverage of the pesticide on the canopy is an ultimate goal. The movement of the air-jet and, hence the trajectories of spray droplets are influenced by the ambient wind. Since most of the air-assisted sprayers apply the pesticide from both sides, a headwind could deflect the air-jet and reduce its velocity while a tailwind enhances its movement. A crosswind (90°) of 5 m/s average speed reduced the velocity of the sprayer air-jet and deflected its direction (toward the wind direction) by an average of 2.0 m/s and 0.5 m at horizontal distance of 2.3 m from the sprayer air outlet, respectively (Endalew et al., 2010). Any changes in the air-jet characteristics due to the wind might have substantial impact on spray deposition on the tree through changing the droplet speed and its trajectory, which might result in less deposition or coverage uniformity.

Droplet size directly affects the droplet speed and trajectory (Bagherpour et al., 2012). Larger droplet sizes (> 400 µm) were faster (4.5 − 8.5 m/s) than smaller ones (< 400 µm) with 0.5 − 2.0 m/s measured at 0.5 m from the nozzle exit (Nuyttens et al., 2007). At the same time, the effect of wind depends on its direction. A crosswind of 135°, measured from the air-jet direction, deflected the air-jet more than the 90° measured at 20 cm from the outlet (Fox et al., 1985).

Different air-assisted sprayers have different airflows. Increasing the airflow could help to transport the droplets to the whole canopy; however, reducing the airflow improved the deposition at the near side of the canopy (Farooq and Salyani, 2004). The characteristics of the airflow determine its behavior under windy condition. Air-jet discharged from a narrower outlet was deflected more than the one discharged from a wider outlet due to the crosswind when they have the same power at the outlet (Fox et al., 1985). Developments of the air-assisted sprayers are ongoing to improve the efficiency of these sprayers. Matching the air-jet velocity and volume to the canopy characteristics is one of the advanced changes to improve the sprayer efficiency (Chen et al., 2012).

Wind effects on the deposition could be different due to the diversity in the air-jet volumes, velocities, and directions of different sprayer designs. In addition, at field conditions, wind speed is changeable and fluctuates within short time. For example, within 20 s only, chosen randomly from the spray time, wind speed changed between 2.7 to 8.2 m/s (Koch et al., 2005). These momentary changes in the wind conditions may alter the droplet trajectory. In addition, it made it difficult to find a significant relationship between the wind conditions and the deposition variability (Nordbo et al., 1993). There is a strong belief in the effects of wind on the deposition distribution in orchards application; however, quantifying these effects is more complicated (Stover et al., 2003; Koch et al., 2005).

Although studying the effect of wind on spray deposition under field conditions could provide more realistic results than laboratory tests, the latter may establish some useful trends under controlled conditions. In addition, conducting field experiments is more expensive and bring in higher levels of uncertainty due to the variability in field conditions (Xu et al., 1998). Specific objectives of this study were to:

1. Determine the effects of ambient wind on the behavior of the air-jet discharged from a simulated air-assisted sprayer.
2. Quantify the effect of the wind on spray deposition under laboratory conditions.

4.1 Materials and Methods

4.1.1 Air-Jet Distortion

4.1.1.1 System simulation

The air-assisted sprayer and ambient wind were simulated using a centrifugal- and an axial-flow fan, respectively. The centrifugal fan operated at one speed. The air-jet was discharged from different rectangular outlet sizes: large (200 cm^2), medium (126 cm^2), and small (90 cm^2). Average air velocities for these outlets were 14.2, 15.0, and 15.3 m/s, respectively. Two sets of straighteners were installed within the air-jet path to reduce its turbulence. Wind was delivered from a rectangular outlet of 20 cm height and 80 cm width at three nominal velocities of 0.0, 1.2, and 2.2 m/s (no, low, and high) and three directions of 60°, 90°, and 120° relative to the air-jet direction. The direction angles were made by moving the centrifugal fan in relation to the axial-flow fan. The wind outlet was divided into six compartments to improve the airflow uniformity across the outlet width.

4.1.1.2 Data collection

A hotwire anemometer (Flow Master, type 54 N60, Dantec Measurement Technology, Skovlunde, Denmark) was used to measure the air velocity. The anemometer sensor was held on an automated mechanism to move back and forth, continuously, on a track perpendicular to the wind direction (Figure 4-1). The sensor moved at speed of 0.04 m/s in both directions along 0.85 m, track length. It also was moved in and out of the device, manually, to create 12 parallel tracks, which covered the measuring area (0.3 m^2). The first track was located at 5 cm in front of the wind outlet and the others were spaced at 2.5 cm for the first 7 tracks and 5 cm for the rest. Measurements were taken at both directions of the sensor movement. Air speed was read at a frequency of 1-Hz and the data was automatically transferred to a laptop computer. Electrical switches were installed at both ends of the track to automatically start and stop transferring the data to the computer. This way minimized the variability in collecting time among treatments. Other electrical switches were installed at the two ends to stop the sensor movement, automatically to improve the work efficiency and safety.

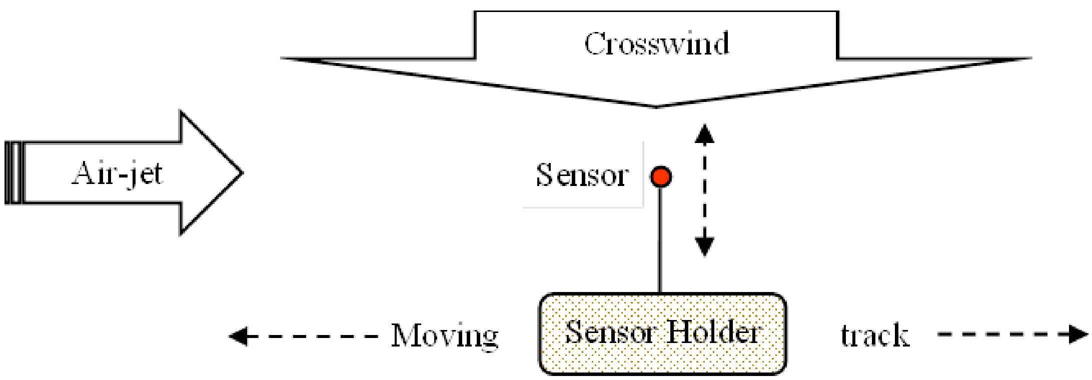

Figure 4-1. Top view sketch of anemometer sensor movement within the measuring area.

4.1.1.3 Sensor angle

The anemometer sensor, used in this experiment, measures the air velocity at one dimension. Therefore, its direction in relation to the air direction could affect its readings. Crosswinds could change the air-jet direction, continuously along its movement; hence changing the air-jet angle will affect the sensor readings. At the same time, keep changing the sensor angle to be perpendicular to the air direction all the time was not applicable. To find an appropriate direction to install the sensor, five direction angles of the sensor (0°, 30°, 45°, 60°, and 90° measured counterclockwise from the air-jet centerline) were tested (Figure 4-2). At each angle, air velocity was measured at fifteen locations (5 tracks × 3 points each) within the measuring area. Locations were spaced at 5.0, 5.0, 7.5, and 10.0 cm between tracks and 20.5 cm within each track. At each location, the air-jet velocity was recorded continuously for at least 35 s at 1-s interval. Readings were recorded in the middle height of the air-jet outlet. Results showed different trends for each angle at different locations. However, as an overall comparison, the angle of 45° recorded the highest velocity average. Thus, the sensor angle was fixed at 45° from the air-jet centerline for all the readings.

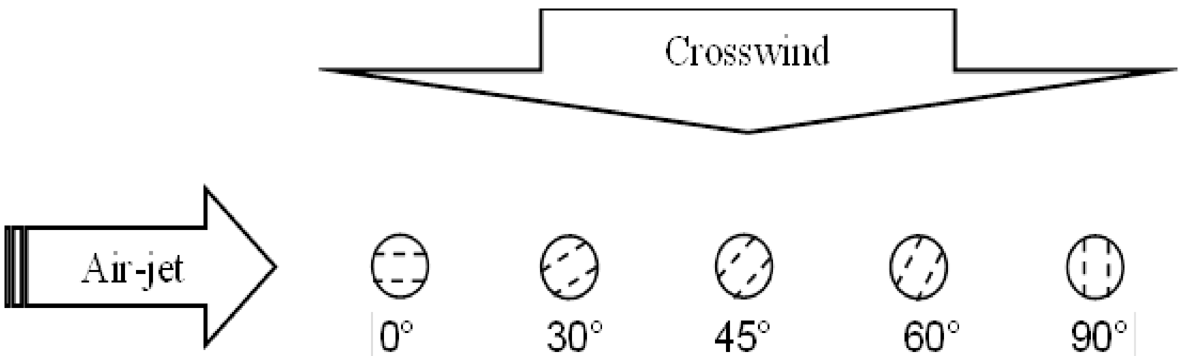

Figure 4-2. Top view sketch of sensor tip angles relative to air-jet direction. Dotted lines represent the tip slots.

4.1.1.4 Air-jet velocity reduction

Figure 4-3 shows the velocity of the air-jet recorded at different tracks along the air-jet centerline. Similar data of each wind treatment were used to create a horizontal contour of maximum air velocities, measured at about 2.5 cm interval along the air-jet direction, to show any distortion in the air-jet (Endalew et al., 2010). A regression line was fitted to the contour points and used to find the reduction in the air-jet velocity. Normalized reduction ratios were calculated by inputting the same start (2.5 cm) and end (82.5 cm) distances into all the regression equations. Velocity changes that happened at no wind were subtracted from the reductions of wind treatments to show the wind effect, only.

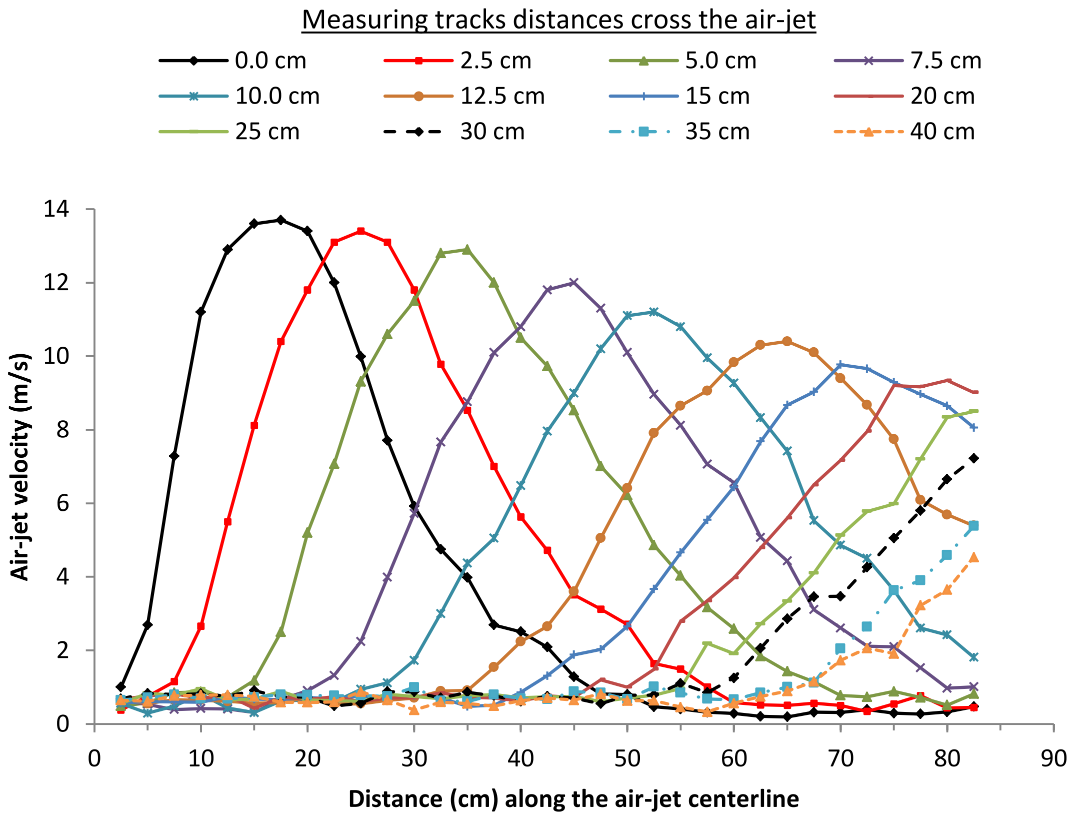

Figure 4-3. Air-jet velocity measured at the 12-tracks under no wind condition.

4.1.1.5 Air-jet direction deflection

Directions of the air-jets were tracked by locating the x- and y-axis of the velocity maximums of air-jet recorded at each treatment. The “Linest” function (Microsoft excels) was used to fit a second order regression curve to the coordinates of each treatment (Figure 4-4). The deflection in the direction of each air-jet was calculated by inputting 2.5 and 82.5 cm to each equation as start and end distances, respectively. Air-jets, normally, move straight at no crosswind. However, if there was any deflection at no wind, it was subtracted from the deflection of other wind velocities to correct any error that might have happened due to some deviation in the direction of the simulated sprayer.

4.1.2 **Deposition Study**

The simulated air-jet and ambient wind systems, used in the study of air-jet distortion, were also used in this section. In addition, a piezoelectric nozzle droplet generator, using orifice sizes of 50, 100, and 150 µm, was used to generate different spray droplet spectra. The nozzle uses an electrical frequency to break up a continuous water stream into droplets at a relatively uniform size. A sinusoid voltage at different high frequencies generated by a Synthesized Function Generator (model Instek SGF-2110, Good Will Instrument Co., Ltd., Taiwan) was used to operate the nozzle.

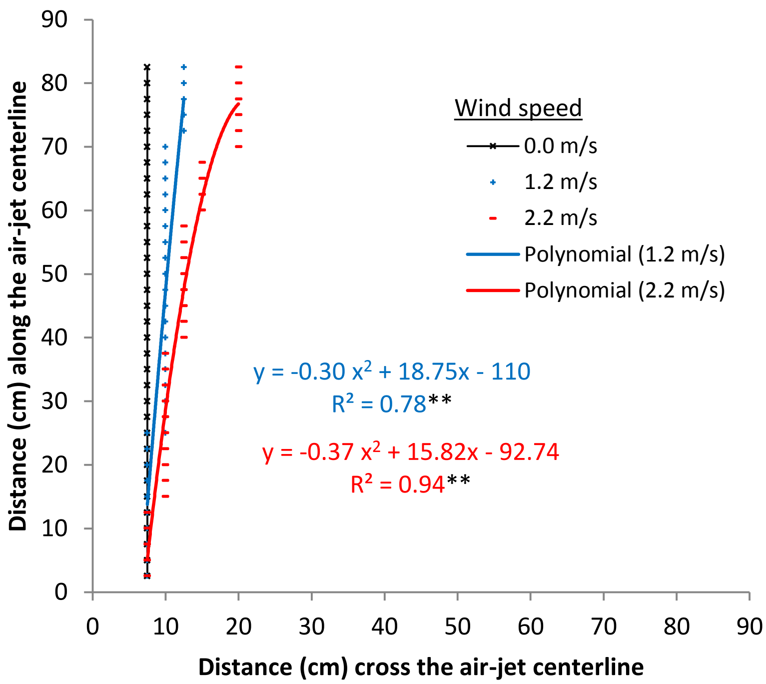

Figure 4-4. Locations of air velocity maximums with regression fits. **=significant at 1% level.

Deionized (DI) water, delivered under a fixed air pressure, was used as spray liquid. The three orifice sizes resulted in mean droplet diameters of 107, 207, and 267 µm, respectively (Table 4-1). Spray droplets were charged with a positive high voltage (0.4 to 1.5 kV, based on the droplet sizes) to separate them and reduce their chance to coalesce (Robert and Threadgill, 1974). Spray droplets were collected on cylindrical targets made of paper towel. Each target was prepared by wrapping a piece of towel (8 × 5 cm) around a PVC pipe section (2.5 × 5 cm) as target holder. Thus, the projection-area of the target was about 12.5 cm^2, which approximates one-third the size of a typical citrus leaf area. The towel was held onto the holder by a specially designed clipper, which eased the replacement of targets. Sprayed targets were collected using pairs of tweezers, put in sealable bags, and weighted with a digital scale (Sartorius Research Model R300s, Data Weighing Systems, Inc. Illinois) to determine the deposition. More details about this method were given by Salyani (1988). The deposition test was conducted at one angle (90°) between the air-jet and the wind centerlines.

Droplet size was determined using an immersion-cell method (Robert and Threadgill, 1974). In this technique, droplets were collected between 2 layers of silicon oils (Dimethylpolysiloxane) of different viscosities, 100 Cs (upper layer) and 60000 Cs (lower layer), respectively. Oil layers prepare a bed to the droplets to maintain their spherical shapes, relatively, and to reduce their chance of evaporation. Spray droplets were collected by moving uncovered immersion-cell within the droplet cloud. The cell was moved immediately and the diameters of ten droplets, chosen randomly, were read under the microscope. Two droplet samples were taken for each treatment. Measured diameters (Di) were input to Equation 4-1 (ASABE Standards, 2012b) to determine the volume mean diameter ($\overline{D}_{33}$) of the spray droplet spectrum. Also, a calculated volume mean diameter (D_C) was obtained from implementing the flow rate (Q) and frequency (F) (corresponding to each treatment) in Equation (4-2) (Salyani, 1988) .

$$\overline{D}_{pq} = \left[\frac{\sum_i D_i^p}{\sum_i D_i^q} \right]^{\frac{1}{p-q}} \tag{4-1}$$

Where, p = 3 and q = 0.

$$D_c = \left[(6/\pi) \times (Q/F)\right]^{1/3} \tag{4-2}$$

4.1.2.1 Droplet trajectory deflection

The deflection of droplet trajectory was determined by sampling the deposition on targets fixed at specific locations and sprayed for certain duration. Eight target locations (P1 to P8), spaced at 5 cm interval for the first 5 locations and 7.5 cm for the remaining locations, were used. The locations were arranged in a line perpendicular to the air-jet direction at 85 cm from the air-jet outlet. Only one target was used a time. Any changes in the system pressure will change the flow rate and the droplet size. Cutoff the flow and restart it between any two followed treatments will change the pressure. To avoid the unwanted changes that might happen in the system pressure, the spray was not shut off during the time of changing targets or treatments. Instead, a special electromechanical device was designed and used to stop the spray during the non-spray time by collecting the spray droplets and redirecting them to a draining container. However, the device moved aside from the droplets stream during spray time. The device is spring-loaded to normally collect the droplets and prevent them from reaching targets. However, using an electrical solenoid and switches, the target holder movement will close and open the electrical circuit to determine the start and stop of the spray.

The spray was started manually and shut down, automatically and its time was controlled by an electrical timer (Dimco Gralab Darkroom Universal Timer - Model 165, Ohio). Sprayed targets were handled as fast as possible with care to minimize the evaporation rate of the water from them. After obtaining the deposition data (using the weighing method), a weighted average was calculated for the highest three deposition values of each treatment to estimate the location of the deposition peak. The locations were used to determine the deflection distance of the droplet trajectory. The deposition peaks recorded at the “No” wind treatment were used as the zero distances and any changes in the locations will be accounted for the wind changes. Thus, all treatments were normalized to have the same starting points (zero).

Table 4-1. Droplet generator system settings for the discharged droplet sizes.

Orifice diameter	Pressure P/SD (kPa)	Frequency F/SD (kHz)	Flow Rate Q/SD (ml/min)	Droplet Mean Diameter[a] D_c/SD (µm)	D_{30} /SD (µm)
50 µm	59.9/ 0.5	21.450/ 0.2	0.96/ 0.03	113/ 1	107/ 2
100 µm	40.2/ 0.7	9.385/ 0.3	2.97/ 0.18	216/ 6	207/ 10
150 µm	39.7/ 1.2	9.460/ 0.0	5.89/ 0.59	270/ 9	267/ 12

[a] D_c= calculated mean volume diameter, D_{30}= measured mean volume diameter, SD= standard deviation.

4.1.2.2 Deposition quantification

To quantify the deposition, spray droplets were collected on targets moving at a relatively fixed speed of 0.03 m/s along the measuring area. At the same moving speed and spray time, spray flow rate delivered from larger orifice size (150 µm) was more than the flow rate of smaller orifice size (50 µm). Hence, the speed was chosen to maximize the deposition without reaching the runoff stage. The depositions of different treatments were normalized based on one flow rate (0.05 cm^3/s). To maximize the deposition collection, targets were moved at three heights (3-cm interval). Based on results of a previous part of this study, the deflection distances were different among different treatment combinations. Thus, the moving distance as well as its start and end positions were set to be different among the wind treatments. Accordingly, the start and stop switches were installed at a sliding plate for easy adjustments. Changing the position of the switches maximized the target exposure time to the spray and minimized its waiting time under no-spray conditions. Sprayed targets were handled in the same way used in the trajectory deflection to obtain the deposition data.

4.1.3 **Experiment Procedure and Design**

The study was conducted in two stages. The first one (started in March 2011) was designed to determine the distortion in the simulated-sprayer air-jet due to ambient wind. The second one (started in January 2012) was designed to study the wind effects on deposition variability through finding the deflection in the droplets trajectories and quantifying the deposition. The distortion experiment was arranged as split-split plot with four replications. Variables of wind directions (60°, 90°, and 120°), outlet sizes (90, 126, and 200 cm^2), and wind velocities (0.0, 1.2, and 2.2 m/s) were tested as main plot, subplot, and sub-subplot, respectively. The trajectory deflection part was arranged as split-split plot with four replications. Orifice diameters (50, 100, and 150 µm), wind speeds (0.0, 1.2, and 2.2 m/s), and target positions (P1 to P8) represented the whole plots, subplots, and sub-subplots, respectively. To quantify the deposition, wind speeds (0.0, 1.2, and 2.2 m/s) and outlet sizes (90, 126, and 200 cm^2) were examined in a factorial experiment with four replications. All studies were arranged in Randomized Complete Block Designs (RCBD). Results were analyzed statistically using “mixed” and “GLM” statements in SAS® software 9.2 (SAS Institute, Inc., Cary, N.C.) and means were compared using the least significant difference (LSD) and the “pdiff” at 5% level of significance.

4.2 Results and Discussion

4.2.1 **Air-Jet Velocity Reduction**

Statistical analysis of the data showed significant reductions in the velocity of the air-jet by changing wind direction, air-jet outlet size, or wind speed. There was also a significant effect of the interaction between these variables on the velocity changes. Figure 4-5 (left) shows the velocity reduction of the air-jet, discharged from different outlet sizes, due to wind effects. The velocity of the air-jet normally declined as it moved away from the outlet. At no wind, the velocities of the air-jets discharged from the large, medium, and small outlets, measured at 0.85 m from the outlet, were reduced by 21%, 33%, and 45%, respectively. The overall velocity averages of the air-jet delivered from the large, medium, and small outlets were 14.2, 15.0, and 15.3 m/s, respectively. Those velocities resulted in airflow of 0.28, 0.19, and 0.14 m^3/s, respectively. The differences between the air velocities were not as large as those of the airflows. Therefore, maintaining the air-jet velocity depends on the airflow more than the initial velocity.

Increasing wind speed increased the velocity reduction of the air-jets for all the outlets. Applying a crosswind of 1.2 m/s further reduced the velocity by 9%, 13%, and 11% for the 3 outlets, respectively. Increasing the wind speed to 2.2 m/s added 18%, 21%, and 22% more reduction to those happened at no wind, respectively. This indicates a positive relationship between wind speed and its effects on the air-jet distortion, especially within the velocity of 2.2 m/s or less. After subtracting the normal decline in the air-jet velocity, wind effects differed based on the outlet sizes. At high wind, the air-jets of both medium and large outlets gave similar reduction, which was significantly higher than the smaller outlet. In contrast, the air-jet of the medium outlet, at the low wind, gave the highest velocity reduction (13%). It was significantly higher than the other two outlets.

Wind effects on the velocity of the air-jet were affected by changing wind direction. Crosswinds coming from the same direction as the air-jet direction have less effect on the air-jet distortion than perpendicular or opposite winds. As wind effect only, the crosswind of 90° resulted in the highest velocity reduction of 19% as compared with 120° and 60°, which resulted in 16% and 11%, respectively (Figure 4-5, right). Both wind velocities followed similar trends over all wind directions.

4.2.2 Deflection of the Air-Jet Direction

Crosswind not only reduced the air-jet velocity but also it deflected its direction. Figure 4-6 shows the changes in the air-jet direction due to the wind effects. The left side of the figure shows a deflection in the air-jet direction due to both wind velocities. Doubling the wind speed resulted in more than twice deflection in the air-jet. An overall average of 10.1 and 4.2 cm deflection in the air-jet direction happened at high and low winds, respectively. At low wind, there was no significant difference in the direction changes among the air-jets of all the outlets. However, at high wind, the air-jet of the small, medium, and large outlets deflected by 12.3, 9.7, and 8.1 cm, respectively.

Thus, increasing the air-jet volume could mitigate the wind effects. Changing wind direction resulted in significantly different deflections in the air-jet direction (Figure 4-6, right). At both wind velocities, wind coming from direction of 60° resulted in the lowest deflection in the air-jet direction as compared with the 90°– and 120°–direction. Crosswinds coming from 90– and 120° resulted in similar deflections in the air-jet direction. Both wind speeds have similar trends for each direction. If these deflections in the air-jet direction due to the wind cannot be eliminated, they need to be considered for adjusting the start and stop of the spray in variable rate sprayers.

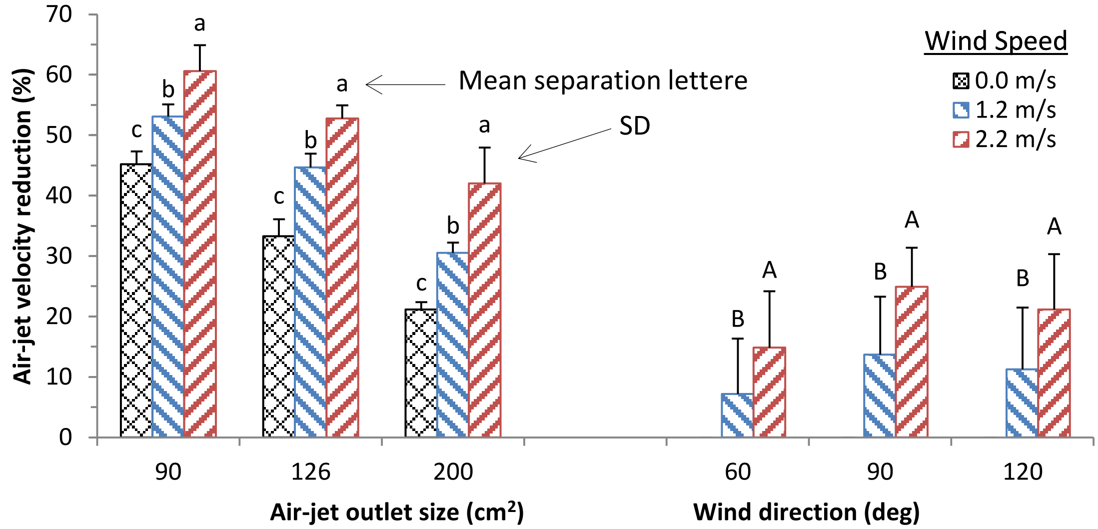

Figure 4-5. Velocity reduction of the air-jet due to crosswind under different air outlet sizes (left) and wind directions (right). Within each outlet size or wind direction, bars with the same letter are not significantly different at the 5% level.

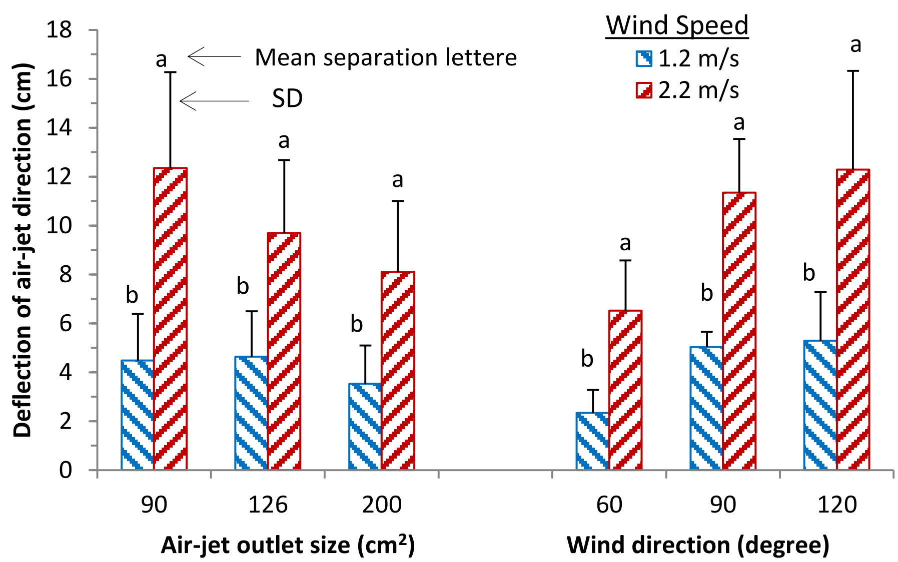

Figure 4-6. Deflection of the air-jet due to crosswind for different air outlet sizes (left) and wind directions (right). Within outlet size or wind direction, each two neighboring bars with the same letter are not significantly different at the 5% level.

4.2.3 **Droplet Trajectory Deflection**

Figure 4-7 shows the deflection in trajectories of different droplet sizes, carried by air-jet delivered from different outlet sizes, due to crosswinds. The right side of the figure shows the trajectories of all droplet sizes where they deflected at both wind velocities. However, their deflection magnitudes between the two wind velocities were different. At 1.2 m/s, trajectories of all droplet sizes deflected within a small range of 3.7 – 3.9 cm. Increasing the wind speed to 2.2 m/s added more deflection and expanded its range for all droplet sizes. The smaller the droplet size is the longer deflecting distance. Droplets of the 107-µm deflected by 9.7 cm as compared with 7.6 cm for the larger droplet (267 µm). Deflection of the droplet trajectory was also affected by the volume of the air-jet (Figure 4-7, left). All trajectories at different air-jet volumes were deflected due to the crosswind. The deflection trends of the three air-jets were similar at the two wind velocities. However, deflection of the droplets increased by reducing air-jet volume.

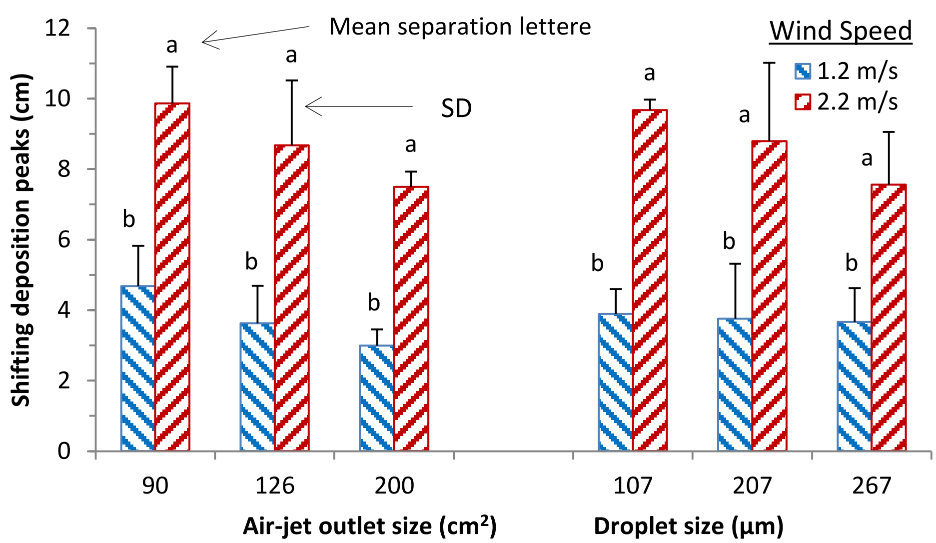

Figure 4-7. Changes in the trajectories of different droplet sizes (right) at different outlet sizes (left) due to crosswind. Within outlet size or droplet size, each two neighboring bars with the same letter are not significantly different at the 5% level.

Studying the behavior of different droplet sizes under different airflows showed different trends. Droplet sizes of 107- and 207-µm behaved similarly under different airflows. Their trajectories deflected more as the airflow reduced. However, droplets size of 267-µm had different trend. Its trajectory deflected less at medium outlet than at large or small outlet. From the results, it was not clear why the air-jet delivered from the outlet 126 cm^2 had less deflection than the 200-cm^2 outlet.

4.2.4 **Deposition Quantification**

To quantify the deposition for each treatment, cumulative water was collected on a moving target along the target locations. Figure 4-8 shows the wind effects on the deposition resulted from different droplet sizes. Over all wind velocities, increasing the droplet size significantly added more deposition on targets. The 107-, 207-, and 267-µm droplet sizes resulted in overall deposition averages of 2.31, 4.24, and 4.71 mg/cm^2, respectively. The deposition of these droplets was significantly affected by the crosswind. Over all the droplet sizes, deposition of 4.38 mg/cm^2 was recorded under no wind condition. Applying a crosswind of 1.2 and 2.2 m/s significantly reduced the deposition by 11% and 32%, respectively. The reduction in the deposition due to the crosswind had similar trends for all droplet sizes. In addition, the reduction in the deposition is proportional to the wind speed and droplet size. Using different sizes of the air-jet outlet did not affect the deposition, significantly. Deposition quantities collected from different droplet sizes did not follow a clear trend over the air outlet sizes. However, reducing the outlet size from 200 cm^2 to 126 and 90 cm^2 resulted in an overall deposition reduction of 5% and 9%, respectively. Changes in the deposition, measured at short distance (0.8 m) from the outlet, could be clearer at farther distances.

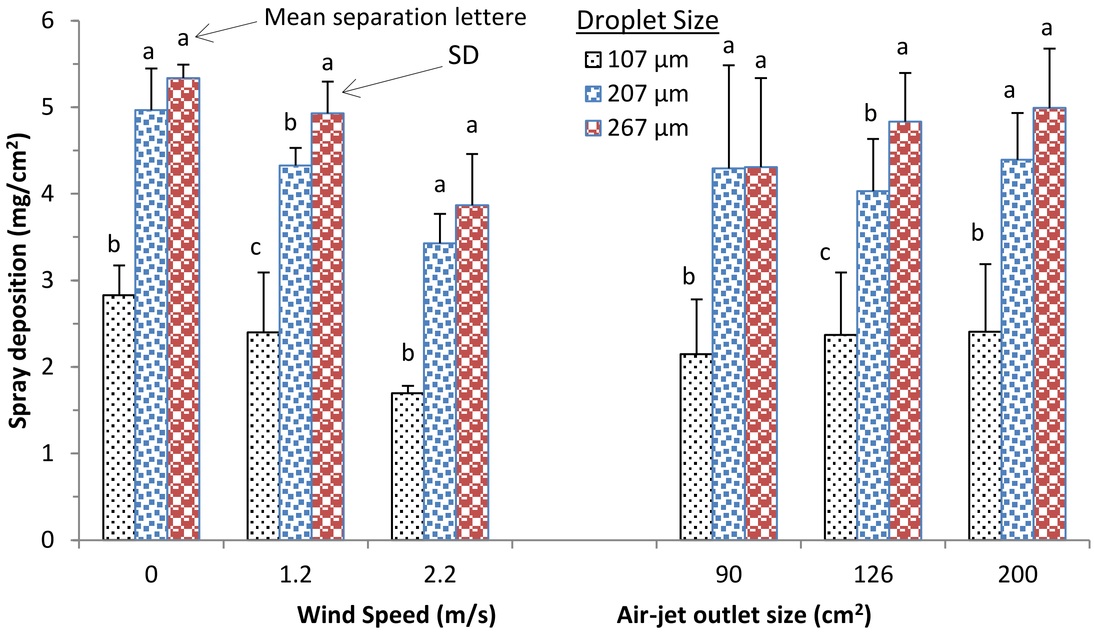

Figure 4-8. Deposition of different droplet sizes under the effect of crosswind (left) and air-jet outlet size (right). Within each wind velocity or air-jet outlet size, bars with the same letters are not significantly different at the 5% level.

Fitting a multiple regression to the droplet size (Ds) and wind speed (Ws) variables to estimate the deposition, (Dep) resulted in the relationship shown in Equation (4-3) with a coefficient of determination, $R^2 = 0.89$.

$$Dep = 0.016\, D_S \quad 0.62\, W_S + 1.46 \tag{4-3}$$

Including the air-jet outlet size (Os) as independent variable did not improve the estimation, and hence it was excluded.

4.3 Uncertainty

Air velocity measured in the laboratory could have some uncertainty due to specifications of the instruments or the test setup. The uncertainty within the air velocity readings could come from the following sources:

1. Sensor resolution error, u_{rs}. It equals to half of the last reporting digit. Since data was reported in m/s at two digits, the resolution error is ± 0.005 m/s.

2. Zero-order uncertainty error, u_0. It represents the expected random error caused by the data scatter around the actual readings. It is estimated as ±1/2 of the sensor resolution. Because, the resolution was ± 0.005 m/s, the zero-order error was ± 0.0025 m/s.

3. Sensor accuracy error, u_a. It is assumed ±0.1 m/s (manufacture specifications).

4. Linearity error, u_l. Since the sensor is measuring the wind velocity indirectly, it assumed to have some linearity error. This error is assumed ± 0.05% of the full reading range. The reading range for the sensor was 50 m/s. Therefore, the linearity error is ± 0.025 m/s.

5. Sensitivity error, u_s. This error could come from the variation of the ambient temperature during the measuring time. However, the temperature within the laboratory was automatically controlled within ± 3°C. In addition, the sensor readings for each run were always completed with a maximum of 35 s. Therefore, this error was neglected.

6. Hysteresis error, u_h. It represents the error in the readings that comes from the upscale and downscale measuring. This error assumed to be less than ± 0.015% of the full reading range. Therefore, it was ± 0.0075 m/s because the full rang was 50 m/s.

7. Repeatability error, u_r. Repeating the measurements at different time at the same conditions may not give the same readings. Thus, the repeatability error was assumed to equal to the standard error (SE) of the readings of the sensor. The sensor was used to measure wind speed at fixed places. The SE of those readings was 0.023 m/s. Therefore, the repeatability error was ± 0.023 m/s.

8. Moving error, u_m. In order to measure wind velocity along the ambient wind outlet, the sensor was moved back and forth at a speed of ≈ 0.025 m/s. This movement creates an error within the wind velocity readings. Thus, the error came from the sensor movement was ± 0.025 m/s.

The overall uncertainty was calculated using Equation 4-4 (Figliola and Beasley, 2006).

$$(u_d)_E = \pm\sqrt{{u_{rs}}^2 + {u_0}^2 + {u_a}^2 + {u_l}^2 + {u_h}^2 + {u_r}^2 + {u_m}^2} \quad (P\%) \tag{4-4}$$

$$(u_d)_E = \pm\sqrt{0.005^2 + 0.0025^2 + 0.1^2 + 0.025^2 + 0.0075^2 + 0.023^2 + 0.025^2} \quad (95\%)$$

$$(u_d)_E = \pm\, 0.11\, m/s \quad (95\%)$$

Now, the overall uncertainty associated with the wind velocity readings recorded in the laboratory by the hot wire anemometer is ± 0.11 m/s.

Based on the results of the laboratory tests, it could be concluded that:

1. A crosswind of 2.2 m/s significantly reduced the air-jet velocity by 20%, measured at 0.85 m from the air-jet outlet. Maximum reduction happened at the 90° direction of the wind than the 60° and 120°.

2. The crosswind of 2.2 m/s deflected the air-jet direction of a small air volume (0.14 m^3/s) by 12.0 cm measured at 0.85 m from the outlet. However, doubling the air volume (larger outlet) reduced the air-jet deflection by 34%.

3. Maintaining the air-jet velocity depends on its volume more than its velocity at the air outlet.

4. The changes in velocity and direction of the air-jet due to the crosswind shifted the trajectory of droplets. The shift was about 10 cm for 107-µm droplet size but reduce by 22% for larger droplets (267 µm).

5. Overall, crosswind of 2.2 m/s reduced the deposition by 32% (measured at 0.85 m from the air outlet); however, the deposition was affected by the droplet size and the wind speed more than the air volume.

CHAPTER 5
VARIATION IN THE DEPOSITION OF AN AIR-ASSISTED SPRAYER DUE TO THE AMBIENT WIND IN AN OPEN AREA

Ambient wind could reduce the number of droplets that reach the targets due to restrictions to the movement of the sprayer air-jet. It could reduce the deposition at upwind side and increase it downwind side. Sometimes, wind could increase the deposition by creating turbulence around targets, which results in putting deposition on both target sides. Wind that comes parallel to the sprayer moving line is expected to reduce the deposition on the targets far away from the sprayer due to deflecting the air-jet and restrict it from reaching the farther targets. However, it increases the deposition on targets close to the sprayer due to moving droplets along the sprayer travel line, which gives more time for the droplets to deposit on targets. Thus, wind could result in a non-uniform deposition, which will affect the pesticide efficacy. In a study to recover spray droplets, conducted in an open area (Theriault et al., 2001), driving downwind recovered about 40% extra droplets as compared with driving upwind. The results show the effects of the wind on the deposition distribution between the two moving directions of the sprayer.

Conducting a spray experiment in an open area, (no trees) will establish clearer trends of the wind effects on the deposition variability than the real citrus grove. In the presence of tree canopies, wind speed will be reduced significantly and its direction might change. At the same time, wind condition within the grove change rapidly. For example, within 20 s only, chosen randomly from a spray time, wind speed changed between 2.7 to 8.2 m/s (Koch et al., 2005). These momentary changes in the wind conditions may alter the droplet trajectory and, hence add more deposition variability. In addition, it made it difficult to find a significant relationship between the wind conditions and the deposition variability (Nordbo et al., 1993). Biological samples (citrus leaves) also will add more variability to the deposition due to the differences in their sizes, ages, and projection angles. The leaves issues could be minimized by using artificial targets that are relatively uniform in their characteristics and sizes and can be installed at comparable distances. In the grove condition, it is not applicable to repeat the spray treatment on the same tree due to the contamination issue; however, with artificial targets in an open area, the cross contamination can be minimized. Improving the spray application efficiency by determining the factors that cause spray variability is the key to reduce the pesticides wastages (Nordbo et al., 1993) and get better pest control. Thus, a spray test was conducted in an open area using artificial targets with the following objectives:

1. Determine the effects of ambient wind on deposition distribution of pesticide on artificial targets in an open area.
2. Examine if the sprayer operating parameters (travel speed and direction) could change the wind effects on the deposition.

5.1 Materials and Methods

5.1.1 **Field Area**

The spray experiment was conducted in an open field in Lake Alfred, Florida on 16-19 July 2012. The field had some dead citrus trees but they were no more than 1.3 m tall. However, the test area was cleaned satisfactorily and there was no tree between targets and the sprayer. There were also no large windbreaks within about 250 m from the filed borders.

5.1.2 **Sampling Locations**

A sampling structure consisting of six PVC pipes, 0.05 × 3 m (Figure 5-1) was designed and used to hold targets at distances of 3, 6, and 9 m, measured from the sprayer-fan centerline, at each side of the sprayer and heights of 1, 2, and 3 m for each distance. Pipes were arranged in line from North to South (three at each side of the sprayer). Each pipe was pivotally connected to a wood base and supported by four ropes at 90° apart. The arrangement allows each individual pipe to be tilted to about 40° from the ground so targets were put and removed easily with no need for ladder. Eighteen targets were sprayed at once for each treatment.

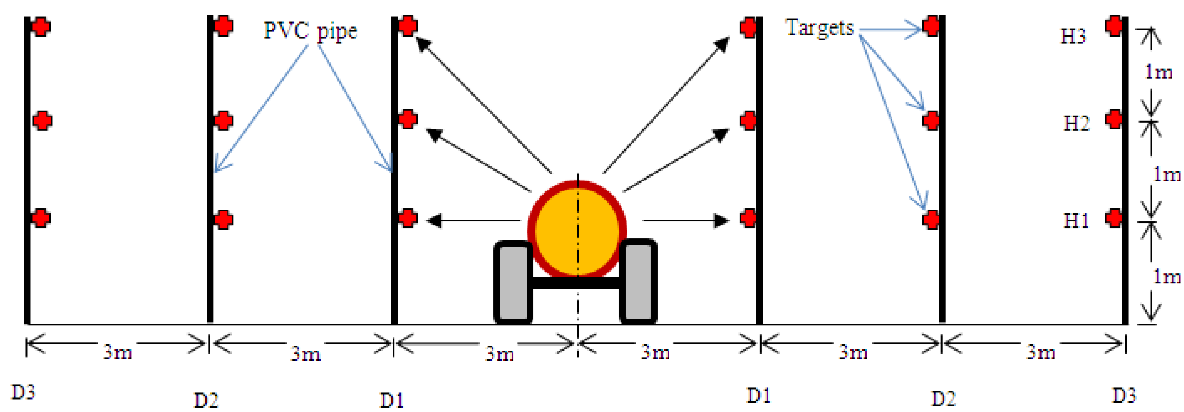

Figure 5-1. Sketch of the target locations in the spray test in open field.

5.1.3 **Target Making**

Targets were made of absorbent tissue paper (Figure 5-2). A piece of the paper (15.2 × 5.2 cm) was folded around a plastic supporter (8.6 × 5.2 cm) to create a target of 7.6 × 5.2 cm area, approximately, leaving about 1cm from top of the plastic supporter uncovered to be used for holding the target. Targets were made of one layer of paper except those used on the first distances (D1s) close to the sprayer, which had three layers to account for more deposition. Another metal supporter (8.6 × 5.2 cm) was added to each target at the first distance from the sprayer to minimize target bending due to the high-velocity sprayer air-jet. Binder clips (Bulldog) were fixed at the pipes and used as target holders to facilitate target exchange.

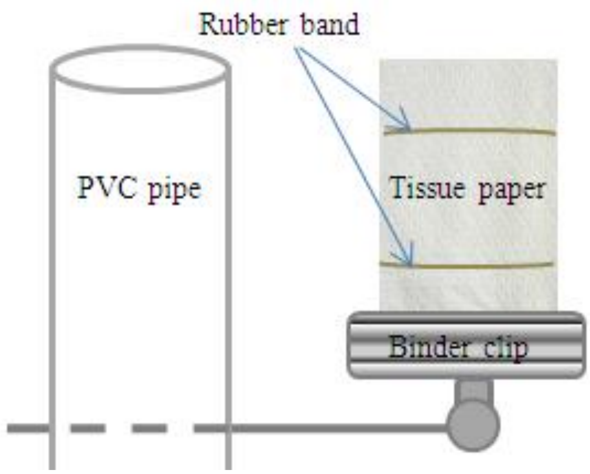

Figure 5-2. Sketch of an artificial target (tissue paper) used in the open field experiment.

5.1.4 **Sprayer and tracer characteristics**

An air-assisted sprayer (Power Blast 500 Sprayer, Rears Manufacturing Co., Eugene, Ore.) powered by the Power Take-Off (PTO) shaft of Ford 7740 tractor (Ford Motor, Dearborn, Mich.) at 540 rpm (1900 engine rpm) was used to apply a tracer of a water-soluble fluorescence dye, Pyranine 10G (Keystone Aniline Corporation, Chicago, Ill.), at a concentration of 1000 mg/L (ppm) (nominal) to the targets. The sprayer has an axial-flow fan (83.8 cm in diameter) and two-exchangeable sets of 24-nozzles (12 each side). Nozzles of each side (12 nozzles) were connected to one separated manifold. Two sets of Albuz ATR, hollow-cone nozzles, Blue and Lilac (Ceramiques Techniques Desmarquest, Evreux, France) were used on the sprayer during the spray experiments. The specifications of these nozzles are shown in Table 5-1.

5.1.5 **Sprayer Calibration**

The air-assisted sprayer (described in Section 5.1.4) powered by the Ford 7740 tractor was calibrated. Only water was used as spray liquid for the calibration. The sprayer was calibrated for both immobile and moving situations.

For the stationary part, the sprayer was stopped at a relatively level ground. It was calibrated for right side, left side, and the both sides for the two nozzle types. All the twelve nozzles at each side were opened. For one-side calibration, the sprayer was operated for about one and five minutes for the Blue and Lilac nozzles, respectively. The fluid pressure was about 1620 kPa (235 psi) and 1000 kPa (145 psi) (nominal) for the Blue and Lilac nozzles, respectively. Changes in the pressure happened due to changes in the pump speed (the pump could operate at two constant speeds and shifting between them was made manually through pulley and v-belt).

Table 5-1. Specifications* of the Blue and Lilac nozzles.

Nozzle Color	Flow rate (L/min)	Nozzle type	Spray pattern	Pan angle	Droplet size ($D_{v0.5}$) ± SD (µm)	Pressure used (kPa)
Blue	3.57	ATR	Hollow-cone	80°	164 ± 5	1000
Lilac	0.48	ATR	Hollow-cone	80°	104 ± 3	1000

*The specifications were cited from (Salyani et al., 2013).

Before starting each run, the sprayer was filled with water to the top edge of the tank inlet. The speed of the tractor engine was raised to 1900 rpm to produce the 540-rpm of the PTO shaft, which is required to operate the sprayer. The system pressure was left for a moment to stabilize and then recorded. The spray was started and stopped manually by the operator. The spray time of each run was recorded using a stopwatch. After stopping the spray, the sprayer was refilled with water to the same level using a nursing tank equipped with a flow meter. The volume of the added water was measured, recorded, and used as the discharged volume for the recorded time. Each run was repeated four times. Switching between the two nozzles types was made by flipping each nozzle holder, manually to shutoff one nozzle and open the other.

However, changing the flow between right-, left-, and the 2-side was made by the operator through manually opening and closing water valves.

For the 2-side calibration, the flow rate for both sides (24 nozzles) was opened and shutoff simultaneously using one (main) water valve. The discharged water was measured using the same procedure described for one side calibration. All the other setting and adjustments such as engine speed and nozzle types were the same as those of 1-side calibration. One difference between the 1-side and 2-side tests was the operating pressure. At 540 rpm of the PTO shaft, the pressure was almost the same for all runs of each nozzle before turning the spray on. However, opening the nozzles of 1-side only or both sides together reduced the pressure by about 2.8% and 6.2% for the Blue nozzle and by 0.0% and 1.4% for the Lilac nozzle, respectively.

For the calibration of the dynamic mode, after filling the sprayer with water, it was run and spray on both sides for a distance of 30.5 m. A flag was put at the point when the spray started. Another flag was put at the corresponding point when the spray stopped. The distance between the two flags was measured using measuring tape. At the same time, the time between start and stop the spray was recorded. After each run, the sprayer was refilled with water. This procedure was repeated four times. The moving calibration was conducted at two travel speeds (1-Low and 3-Low of the tractor gearbox setting), which gave an average travel speed of 2.14 and 4.64 km/h, respectively. The moving calibration was made using Blue nozzle, only with all nozzles (24) opened. The test was conducted on a ground similar to the one of the citrus grove spray experiment.

The flow rate (volume per time unit) of the sprayer for a 1-side or 2-side is the volume of water discharged from that side or both divided by its corresponding time. Similarly, the travel speed of the sprayer was calculated from dividing the travelled distance (30.5 m) by the corresponding time. The flow rate was normalized based on the actual reading of the liquid pressure through Equation 5-1 (ASABE Standards, 2012a).

$$\frac{P_2}{P_1} = \left[\frac{Q_2}{Q_1}\right]^2 \qquad (5\text{-}1)$$

Where:

Q_1 = Flow rate recorded at pressure P_1

P_1 = Calibrated operating pressure

Q_2 = Normalized flow rate at pressure P_2

P_2 = Nominal operating pressure

5.1.6 **Data Collection**

During the spray treatments, the sprayer was traveled at two nominal speeds: slow (2.0 km/h) and fast (6.0 km/h) at two reversed directions: West-East and East-West using two nozzle types, Blue and Lilac. Eight combination treatments (Nozzle × Speed × Direction) were used. Spray was applied from both sides of the sprayer at once and all the twelve nozzles on each side were open. After about five minutes waiting after spray, PVC pipes were tilted so the contaminated targets were reached and collected, manually without using a ladder. Each target was collected by inserting it directly into a sealable plastic bag then released it from the holder. Bags were sealed and stored in an icebox before taken them to the laboratory for analysis. To minimize the cross contamination, target holders were wiped dry by rags before putting new targets. In addition, target holders were directed upward to minimize the runoff contamination upon the targets. Another set of new targets were put in their holders and the pipes were set back to their vertical direction to be ready for the next run. Spray was started at 5 m before targets line and shut off at 5 m beyond the line. Another 10 m distance was left on both sides of the spray area for the sprayer to stabilize its ground speed. Spray starting and ending time were recorded and used for extracting the appropriate wind conditions. Two tank samples were taken before and after spraying of each day. Operating pressure was recorded for both nozzle types at open and closed conditions for each day. The experiment was conducted at randomized complete block design (RCBD) at six replications.

5.1.7 **Weather Data Collection**

A weather station (Figure 3-1) was set up at 30 m to the East of the target line and 10 m to the South of the sprayer traveling line. Wind velocity and direction were recorded at 10 and 3 m heights at 1-s interval. Recorded data were downloaded to a laptop computer, regularly. The data logger time was synchronized with the time of the stopwatch (used to record the spray time for each treatment, manually) to be able to extract the specific wind conditions for each spray treatment.

5.1.8 **Data Analysis**

Samples were kept in the refrigerator while waiting to be analyzed. They were analyzed by replication using fluorometric analysis. A Turner fluorometer (model 111, Turner Designs, Sunnyvale, CA) was used to read the fluorescence concentrations in the sample solution, say in FLX. The fluorometer reads the concentration at 1x, 3x, 10x, and 30x magnitudes. Fluorescence of standard solution samples (made of stock solution has a concentration similar to the tank solution and less) was read at more than one magnitude of the fluorometer. The readings were used to establish converting factors between the adjacent magnitudes as follow: 30x/10x = 3.01, 10x/3x = 2.83, and 3x/1x = 3.05. However, other relationships, 30x/3x = 8.53, 10x/1x = 8.64, and 30x/1x = 26.00, among these magnitudes were established by multiplication.

Based on the expected tracer concentration at each sample, different volumes of deionized water (DI) were used to wash the tracer from targets. Two samples (about 10 ml) of the liquid of each washed-target were taken and two readings were recorded for each sample. Some samples of high concentration were diluted with DI water to bring their tracer concentration to a readable range. Using the established converting factors among the fluorometer magnitudes, samples fluorescence was converted to readings at 1x magnitude. A comparable tracer concentration (FLX_{comp}) for all samples was calculated using Equation 5-2.

$$FLX_{comp} = \frac{FLX \times w \times d}{A \times 1000} \tag{5-2}$$

Where FLX_{comp}, w, d, and A are the deposition per square centimeter, washing water volume (ml), dilution factor, and the target area (39.5 cm^2), respectively. The sample readings were corrected by subtracting the deposition collected from blank (unsprayed) samples. The standard solution readings were also used to establish a regression relationship between the fluorescent reading (FLX) and the equivalent dye concentration (y) in µg/L (ppb) (Figure 5-3).

The regression analysis fitted the relationship between the fluorescent reading (FLX) and the equivalent dye concentration (µg/L) in Equation 5-3. Thus, the comparable deposition readings (FLX_{comp}) were converted to depositions (y) in µg/cm^2 using Equation 5-3.

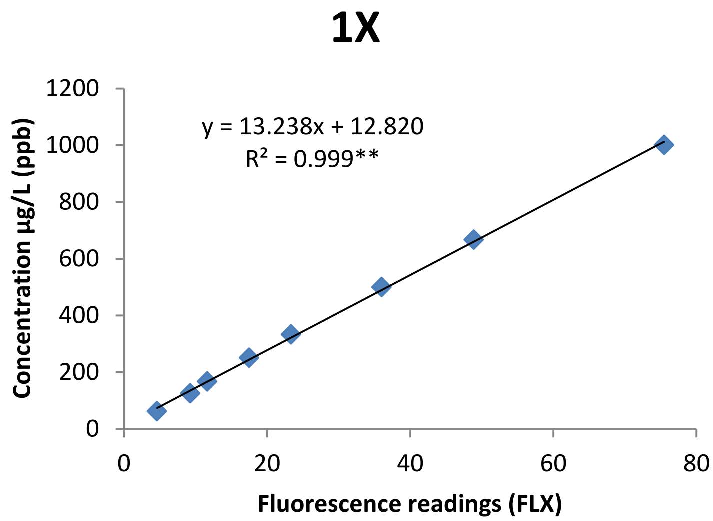

Figure 5-3. The relationship between fluorescence readings at 1X and the dye concentration µg/L (ppb). **=significant at 1% level.

$$y = 13.238\ Flx_{comp} + 12.820 \tag{5-3}$$

The deposition values were normalized based on the actual travel speed (2 km/h nominal), dye concentrations in the tank samples, and the nozzle flow rates. Final deposition values were statistically analyzed using SAS 9.2 software (SAS Inc.). Treatment deposition means, standard deviation (SD), coefficient of variation (CV), and ratio between means of different treatments were used to compare among the deposition at different treatment combinations. A regression analysis was used to establish any relationship between the wind conditions and the deposition variability among different treatments.

For a comparison between depositions collected on targets of two opposed distances, say 9.0 m to the right side and 9.0 m to the left side of the sprayer, regression fit between the two distances was calculated. Average deposition of the three heights was calculated.

One way of finding the wind effect on the deposition variability was done by relating the x- or y-axis components of wind to the deposition collected on two sampling distances measured symmetrically to the right and left sides of the sprayer. However, to clear any relationship with uneven discharge of the sprayer on both sides, ratios between the farthest two locations to the nearest location of one side were calculated.

Wind velocity and direction, recorded during each spray treatment were averaged and used to explore their relationships with the deposition variability among treatments. Based on the recorded wind conditions, wind will be named as Parallel and Crosswinds for those moved relatively parallel and perpendicular to the sprayer traveling line, respectively. Wind did not come exactly parallel or perpendicular to the sprayer traveling line. However, only treatments that have a wind direction within ± 45° (45° to 135° for the parallel and 315° to 45° for the crosswind) from the prevailing average of each group will be included in the category. The x-axis and y-axis component of the wind in each category will be used as parallel and crosswind, respectively.

5.2 Results and Discussion

5.2.1 Sprayer Calibration

Table 5-2 shows the results of the stationary sprayer calibration. Based on opening nozzles on both sides of the sprayer, Blue and Lilac nozzles delivered 102.9 and 12.3 L/min, respectively. The ratio between these flow rates was used to normalize the deposition of these nozzles of the field experiments. Testing the flow rate of each side separately showed no significant difference between the right side (52.4 L/min) and the left side (55.2 L/min) of the sprayer for the Blue nozzle. However, at the Lilac nozzle, the right side gave higher flow rate (6.4 L/min) than the left side (5.9 L/min). The difference between the two sides could be related to the difference in the flow rate between the nozzles themselves because they were used for different times before this experiment.

Table 5-2. Flow rate (L/min) for the Blue and Lilac nozzles at both sprayer sides.

Reps	Blue (L/min)			Lilac (L/min)		
	Right	Left	2 sides	Right	Left	2 sides
R1	52.8	51.1	103.6	6.3	5.8	12.4
R2	52.4	54.2	102.3	6.5	6.1	12.4
R3	52.1	51.9	102.1	6.3	5.8	12.0
R4	52.3	51.7	103.7	6.4	5.7	12.4
Mean	52.4	52.2	102.9	6.4	5.9	12.3
SD	0.3	1.4	0.8	0.1	0.1	0.2
CV	0.6	2.6	0.8	1.0	2.3	1.4

At the moving calibration, the sprayer was tested for the Blue nozzle, only. The sprayer delivered an average flow rate of 105.8 L/min, which is significantly higher than the flow rate (102.9 L/min) of the stationary test. However, the flow rate was not significantly different between the travel speeds of 2.1 and 4.6 km/h. Increased the flow rate at the sprayer movement could come from changes in the engine rpm due to the sprayer travel.

5.2.2 **Wind Condition**

During the test, ambient wind never came from North. Therefore, targets on the north side collected more deposition than those on the south side. The overall deposition ratio between the north side and the south side averaged 3.6. However, the ratio was 1.2 when crosswind was about zero and almost doubled when wind increased to 3.0 m/s (Figure 5-4).

5.2.3 **Crosswind**

To account for the crosswind effect on the spray deposition, the y-axis component of the wind speed (wind speed × cosine of wind direction) was calculated and used as a crosswind. However, some wind speeds that have directions almost parallel to the sprayer moving line (west east) were excluded because they might contradict with the crosswind effect. Since most of the wind (during the test) came from the south direction, the word Upwind and Downwind will be used to describe the south and north sides of the experiments, respectively. The deposition values and their ranges were reduced by computing a logarithm ($\log_{10}$) for them. Wind effects on the deposition in the upwind and downwind sides were made by running a regression analysis between the wind speed and the deposition collected at the same distances (3.0, 6.0, and 9.0 m) from both sprayer sides. Due to the difference between the deposition resulting from the Blue and Lilac nozzles, the deposition of each nozzle was plotted separately.

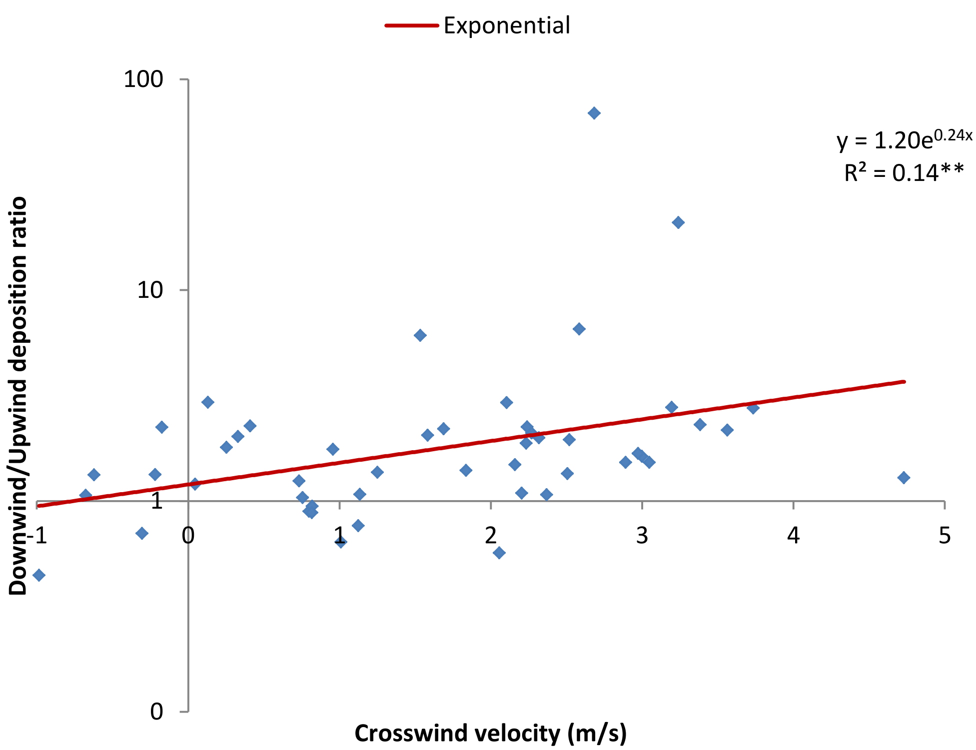

Figure 5-4. Wind effect on deposition ratio on both sprayer sides. **= significant at 1% level.

Figure 5-5 shows the relationship between the wind speed and the deposition collected upwind (dotted line) and downwind (solid line) at 3.0 m from the sprayer centerline. For both nozzles, increasing the wind speed resulted in more deposition on both upwind and downwind sides. The deposition on the downwind targets came from more spray droplets brought by the wind or at least not deflected away from the targets. However, at upwind targets, wind deflected the droplet trajectories into a relatively reversed direction, hence putting extra deposition on the backside of the targets (visually observed). The deposition changes on both sides and nozzles have similar trends. Linear relationships were established between the deposition changes and the wind speed; however, the high variability in the deposition resulted in low values to the coefficients of determination (R^2s) of these regression fits.

Moving farther to a distance of 6.0 m away from the sprayer, the effect of the crosswind on the deposition was different between upwind and downwind sides (Figure 5-6). Deposition at both upwind and downwind sides was similar at low wind velocity (0 to 0.5 m/s). Increasing the wind speed differentiated the deposition between the two wind sides. At the upwind side, increasing the wind speed reduced the deposition on targets of both nozzles. The wind restricted some spray droplets from reaching the targets. However, increasing the wind velocity enhanced the deposition recorded at targets in the downwind area. Faster wind moved droplets to farther distances downwind from the sprayer. In addition, increasing the wind speed resulted in higher variability in the deposition among the upwind treatments. Changes in the variability in upwind area agreed with results found by Theriault et al. (2001).

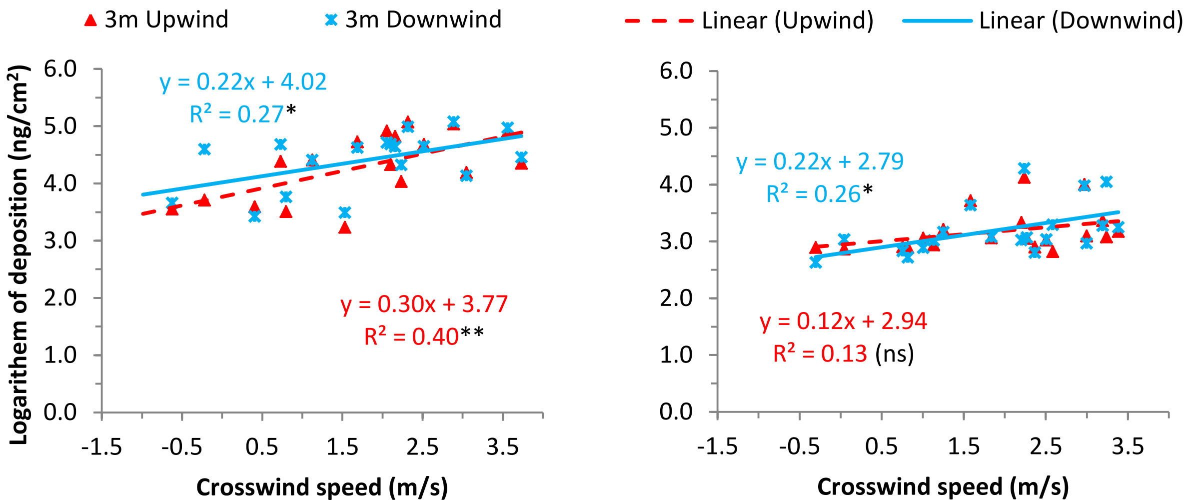

Figure 5-5. Wind effect on deposition at 3 m distance from both sides of the sprayer for Blue (left) and Lilac (right) nozzles. * and **= significant at 5% and 1% levels, respectively. (ns) = non-significant at 5% level.

Examine the wind effects on the deposition variability at the farthest distance (9.0 m) from the sprayer showed more effects of the crosswind on the deposition (Figure 5-7). Similar to the one measured at 3.0 and 6.0 m, the fitting lines intersected at about zero wind speed showing the equality of the deposition between the upwind and downwind sides. However, increasing the wind speed resulted in more diverging between the two regression lines. The deposition in the upwind area reduced as the wind speed increased. A crosswind speed of 1.5 m/s or higher reduced the deposition at the 9.0 m distance upwind to almost 10 ng/cm^2 deposition as compared with a 1000 ng/cm^2 or more at the downwind targets. The wind stopped the spray droplets from reaching the targets located at 9.0 m upwind while transported more droplets towards the downwind targets. Changes of the deposition at both upwind and downwind had similar trends for Blue and Lilac nozzles. These changes in the deposition due to the wind measured at 9.0 m upwind and downwind were sharper and less variable than those happened at 6.0 or 3.0 m distances. Thus, it is very clear how the crosswind differentiated the deposition between the two sides of the sprayer. Changing the deposition uniformity will affect the effectiveness of the sprayed chemical and hence, controlling the pest in the groves.

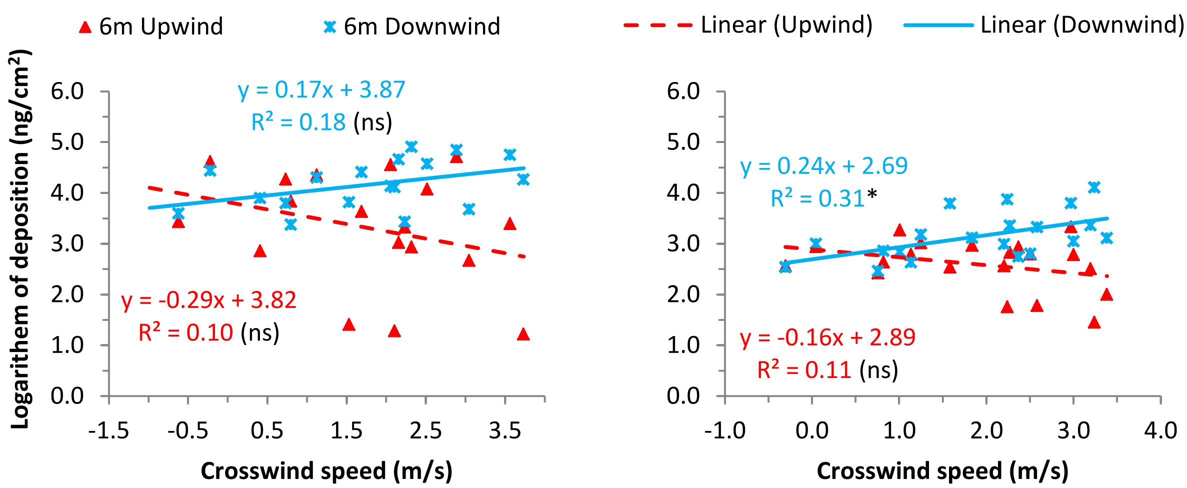

Figure 5-6. Wind effect on deposition at 6 m distance from both sides of the sprayer for Blue (left) and Lilac (right) nozzles. *= significant at 5% level. (ns) = non-significant at level 5%.

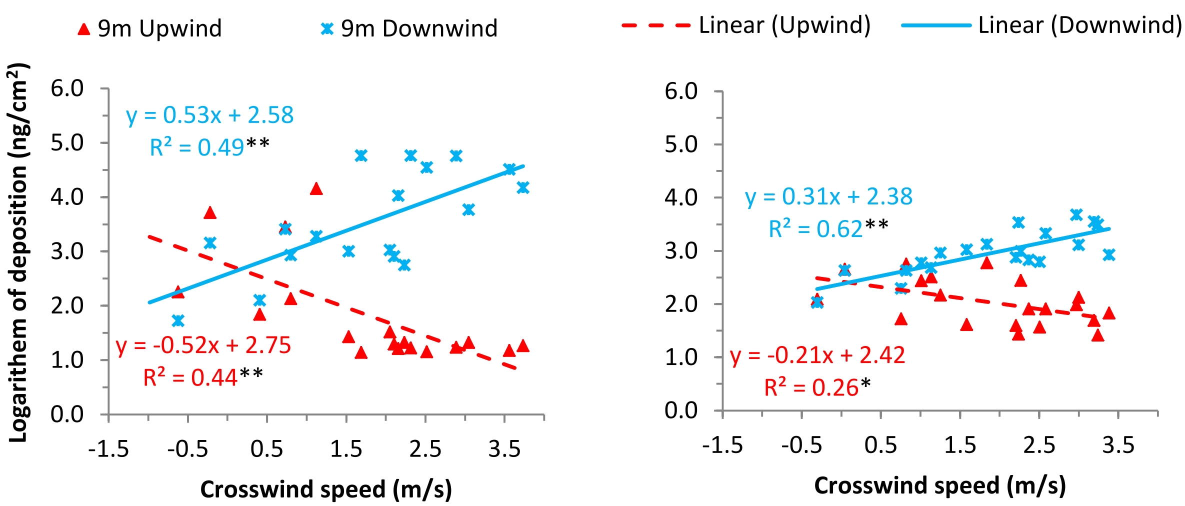

Figure 5-7. Wind effect on deposition at 9.0 m distance from both sides of the sprayer for Blue (left) and Lilac (right) nozzles. * and **= significant at 5% and 1% levels, respectively.

5.2.4 **Parallel Wind**

Parallel wind term was used to represent the wind speed component (wind speed × sine of wind direction) moving parallel to the sprayer travel line (west east). Figure 5-8 shows the effects of the parallel wind on the deposition from Blue and Lilac nozzles measured at 3.0 m to the north and south sides of the sprayer. For both nozzles, increasing the wind speed slightly reduced the deposition on the two sprayer sides. The reduction was the same for both sides. However, the coefficients of determination (R^2s) of the regression lines were low also due to the high variability in the deposition of different treatments.

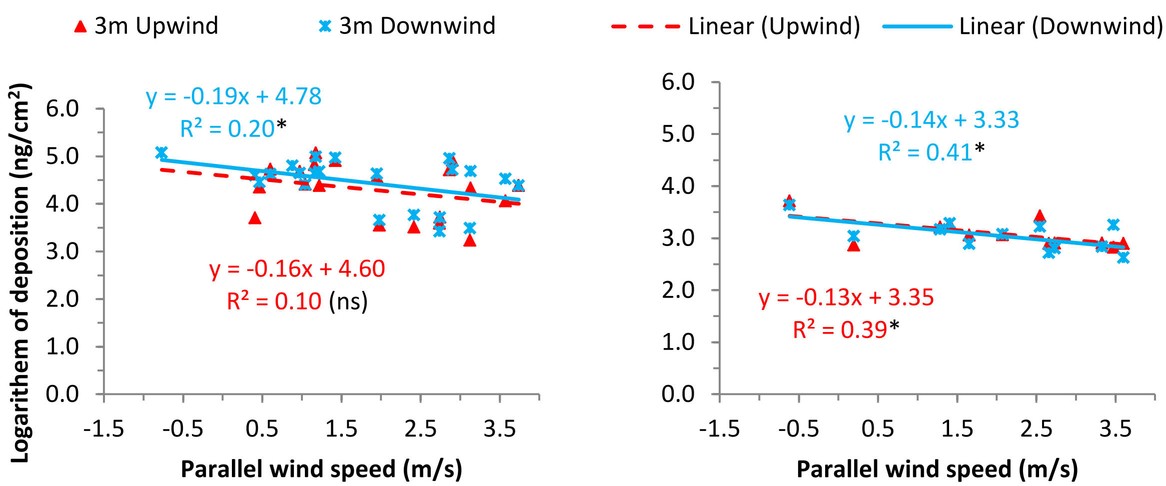

Figure 5-8. Effect of parallel wind on deposition at 3.0 m distance from both sides of the sprayer for Blue (left) and Lilac (right) nozzles. *= significant at 5% level. (ns) = non-significant at level 5%.

Moving for another three-meter away from the sprayer, the effects of the parallel wind increased (Figure 5-9). The wind reduced the deposition at both sides of the sprayer; however, these changes were different between the two nozzle types. Increasing the wind speed reduced the deposition in both upwind and downwind sides for both nozzle types (with lesser slopes for Lilac nozzle fitting curves). However, at downwind side, the relationships between the deposition and wind speed were stronger (higher R^2s) than those in the upwind side.

Wind effects on the deposition were higher at the farthest distance (9.0 m) than at the 3.0 and 6.0 m (Figure 5-10). For the Blue nozzle, deposition on both sides decreased sharply by increasing the parallel wind speed. At wind speed of 1.5 m/s or more, the deposition decreased to almost 10 ng/cm^2. However, the reduction at north side was less for the Lilac nozzle. There was no clear trend of change in the deposition of the Lilac in the south side. At farther distances from the sprayer, the sprayer air-jet speed normally declined; therefore, it will be more vulnerable to the wind effect (Brazee et al., 1981).

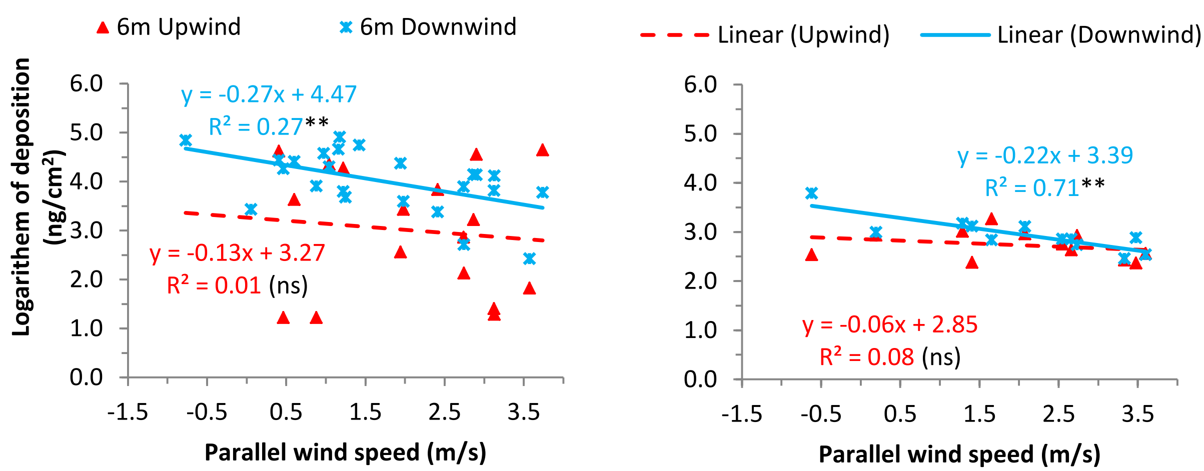

Figure 5-9. Effect of parallel wind on deposition at 6.0 m distance from both sides of the sprayer for Blue (left) and Lilac (right) nozzles. **= significant at 1% level. (ns) = non-significant at level 5%.

5.2.5 Driving Direction

The direction of the sprayer relatively to the wind direction could affect the deposition uniformity within the grove. At regular moving of the sprayer, the air-jet on both sides will be deflected backwards and the deflection rate depends mainly on the travel speed. However, ambient wind that moves parallel to the sprayer direction could affect the deposition uniformity between the two opposite routes of the sprayer. Moving toward the wind (headwind) will add more deflection to the air-jet while driving with the wind (tailwind) will mitigate the wind effect on the air-jet.

Figure 5-11 shows the effect of parallel wind on the deposition under two moving directions. Increasing the headwind speed reduced the overall deposition collected from both sides of the sprayer. The wind added more deflection to the sprayer air-jet and hence, some droplets did not reach the targets. On the other side, increasing the tailwind speed could deflect the air-jet but in a direction opposite to the one resulted from the sprayer travel. This will mitigate the travel speed effects and will enhance the deposition on the farther targets. The variation of the wind effect on the deposition between the headwind and tailwind will change the deposition uniformity within the grove. For example, at the same wind speed of 3.0 m/s, the predicted deposition with tailwind will be 1.2 times that with headwind.

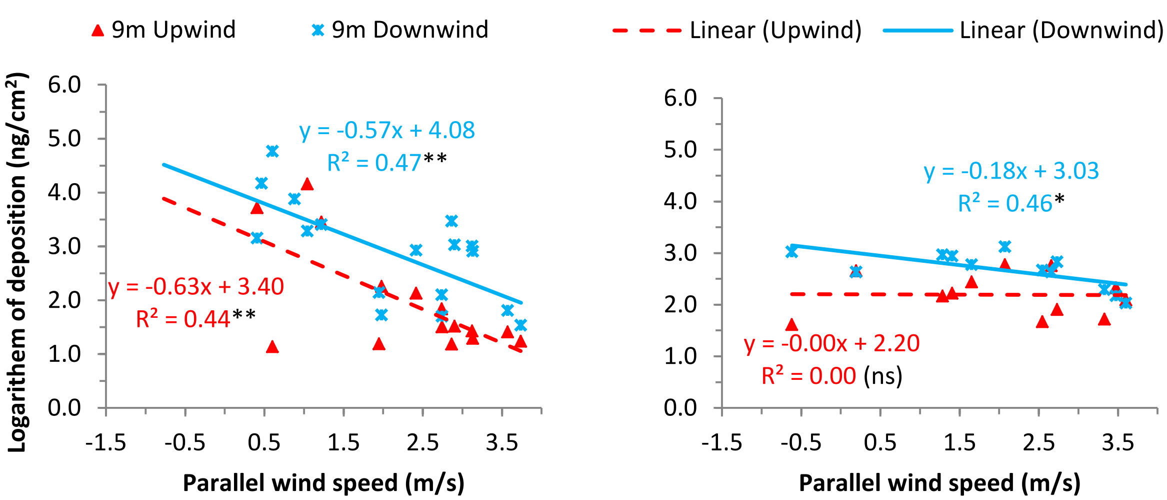

Figure 5-10. Effect of parallel wind on deposition at 9.0 m distance from both sides of the sprayer for Blue (left) and Lilac (right) nozzles. * and **= significant at 5% and 1% levels, respectively. (ns) = non-significant at 5% level.

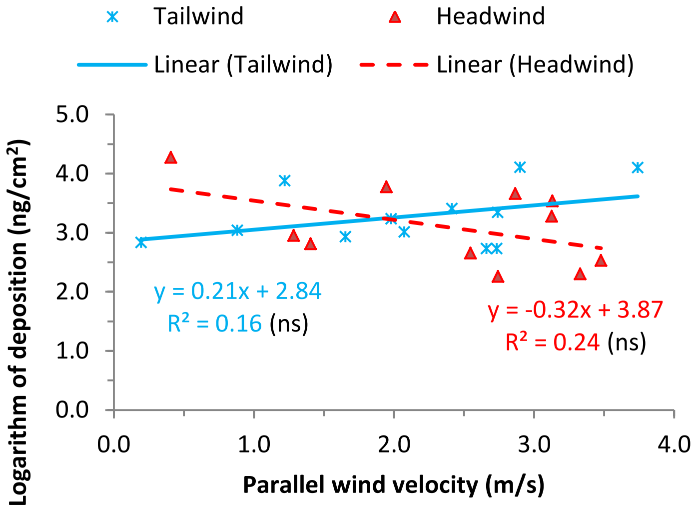

Figure 5-11. Parallel wind effect on the deposition under headwind and tailwind. (ns)= non-significant at 5% level.

The results of the open area test indicated that:

1. Increasing crosswind increased the deposition within a 3.0-m distance in both sides of the sprayer. Spray droplets were deposited on both sides of the upwind targets while deposited on only spray side, downwind.

2. Beyond 3 m from the sprayer, the crosswind increased the deposition downwind while decreasing it upwind. These changes in the deposition increased as wind speed increased. In addition, the deposition variability upwind was higher than downwind.

3. At target distances of 3, 6, and 9 m from the sprayer, increasing crosswind velocity from 0.0 to 3.0 m/s changed the deposit ratios (predicted downwind/upwind) from 1.1, 1.0, and 0.9 to 1.0, 1.5, and 3.5, respectively.

4. For the same wind velocity range (0.0 - 3.0 m/s), winds parallel to the sprayer travel direction reduced the predicted deposition by 11%, 16%, and 48% at 3, 6, and 9 m sampling distances (on both sides of the sprayer), respectively.

5. Wind effects on the deposition interacted with the sprayer travel direction. When sprayer was travelling toward the wind (headwind) increasing the wind velocity from 1.0 to 3.0 m/s reduced the deposition by 18% while deposition increased by 14% for the opposite travel direction (tailwind).

CHAPTER 6
WIND EFFECTS ON SPRAY DISTRIBUTION IN CITRUS

Spray deposition on citrus tree canopies needs to be uniformly distributed over the canopies in order to accomplish its purpose of controlling pests. Any violation to this condition may result in less efficacy of the spray and hence, unsatisfactory pest control. Spray usually applied to the citrus trees with the assistance of air-jet to improve its penetration into the canopy and transport the droplets to farther canopy parts. Conducting a study in the laboratory or in an open-area could give some ideas about the deposition changes due to the wind. Such information is very helpful in planning the actual spray application. However, these studies do not representing the actual field condition. Information that is more reliable could be obtained from studies with all the conditions and variables are real. It could be difficult to find significant results for all the parameters; however, it is the real situation for every spray application. During the spray application, a sprayer travels back and forth between the tree rows. Changing the sprayer direction will change the wind effect and hence could vary the deposition between the two routes due to the wind effects. Ground speed of the sprayer could affect the deposition due to its interaction with the wind effect. The interaction between the ground speed and meteorological conditions and its effect on the spray deposition needs to be investigated (Hoffmann and Salyani, 1996). The objectives of this part of the study were to:

1. Determine the effect of ambient wind on the spray deposition in citrus groves.
2. Quantify the spray variability caused by the ambient wind.

6.1 Notes From the Preliminary Test in Open Field

1. Results of the open-area test showed a significant difference between the deposition means of the Blue and Lilac nozzles, which could shield the significance of some noticeable difference that happened between some other treatments due to the wind

effects. Thus, the Blue and Lilac nozzles were used in this study, separately in order to detect any significance of the wind effects.

2. Studying the wind velocity and direction changes in the citrus grove showed low corresponding wind velocity recorded at the lowest 2/3 height of the tree canopy to the wind recorded at 10-m height. Therefore, the samples will be collected from 2.0 and 3.5 m heights.

3. From the preliminary test, it was difficult to identify the effect of travel direction on the deposition because all targets were in one line and being sprayed at once. Therefore, deposition was sampled from one tree before and one tree after the spray area to account for the movement of the spray droplets due to the wind.

4. From the preliminary test in the open area, spray deposited more heavily on targets near to the sprayer than those located far away from the sprayer. In addition, wind effect on the deposition at the nearer targets was not noticeable as compared with the one at the farther targets. The deposition is more likely to run off the leaf targets located in this area (Hoffmann and Salyani, 1996). Therefore, samples collected from the canopy side adjacent to the sprayer were not processed directly in the mean comparison.

5. Although, the deposition was heavy on targets close to the sprayer, it was very low at 9.0 m from the sprayer at headwind area. Thus, the dye concentration for the tank liquid for this test was kept at 1000 mg/L (ppm).

6. From the preliminary test, it was reasonable to operate the sprayer at 2.0 and 6.0 km/h with good control by the operator. Therefore, the sprayer was also operated at the same travel speed (2.0 and 6.0 km/h) of the preliminary test.

7. Since wind conditions were changing rapidly, wind velocity and direction need to be recorded on the go by an ultrasonic sensor installed on the tractor itself if that is possible. However, due to the unavailability of the instruments and the complexity of using them, wind conditions were recorded at one location in the grove.

8. From the preliminary test, there was a lack in the repeatability of wind conditions for the same treatment. Therefore, more replications (6 or more) are needed. However, the field experiment was set for six replications only due to the unavailability of such large grove and the uniformity of group of at least 15 trees to conduct each treatment.

6.2 Materials and Methods

6.2.1 **Grove Description**

A field experiment was started on 28 November 2012 in about 11 ha of Valencia orange grove (28°05'26.11" N, 81°44'56.58" W) in Auburndale, Florida. The trees were planted at 3.6 × 7.5 m within and between rows, respectively. The average height of the tree was 4.0 m. The tree rows were planted in a north-south direction. There were some missing trees with many resets. Therefore, the canopies along the whole grove were different in their heights, diameters, and densities. The plot size for each treatment was 15 trees (3 rows × 5 trees each). Therefore, it was very hard to find a minimum of 720 trees (48 plots × 15 trees each) that are similar in their characteristics to conduct the experiment. Thus, trees were chosen to minimize the variability among them for each plot as much as possible. In addition, the grove was divided relatively to six areas based on the tree conditions and each part was assigned as one replication.

6.2.2 **Data Collection**

An air-assisted sprayer, driven by a tractor PTO shaft (both were described in Chapter 4) was used to conduct the experiment. Spray was made from the right side of the sprayer, only. Spraying from both sides requires larger treatment plots (at least four rows) which was difficult to establish. All the twelve nozzles of that side were used. The sprayer was driven in two direction (North-South and South-North) at two travel speed (2.0 and 6.0 km/h). Two nozzle types: Blue and Lilac were used to apply a Pyranine 10G tracer at a nominal concentration of 1000 mg/L (ppm). Nozzles specifications are shown in Table 5-1. Four treatment combinations (2 travel speeds × 2 travel directions) were randomly assigned to the plots of each replication. Blue and Lilac nozzles were tested as two separate experiments. The experimental design for both nozzles was factorial in RCBD with six replications.

For each treatment, a minimum of 15 trees (3 rows × 5 trees each) were chosen to represent one plot. Three trees within the middle row on the right side of the operator were sprayed leaving one border tree at each side. However, tracer was sampled from both first and second tree rows. Samples were collected from five locations (L1 to L5) at two heights (2.0 and 3.5 m) for each location (Figure 6-1). The locations, L1 and L2 were assigned to the inner and outer sides of the middle sprayed-tree in the first row. Similarly, the locations, L3, L4, and L5 were located at the inner side of the middle tree, second tree before, and second tree after the middle tree in the second row (not sprayed directly), respectively.

About five to seven leaves (based on their sizes) were collected from each location. They were collected from the outside of the canopy. The leaves were inserted into a pre-marked, sealable bag then put in an icebox before transferring them to the laboratory's refrigerator. A ladder was used to reach the upper height. Ribbons of different colors (varied based on the treatment type) were placed on the trees to mark the start and stop points of the spray. Starting the spray and stopping it were made manually by the sprayer operator. Operating pressure and the spray time were recorded for each treatment. Sprayed trees were left to dry (30 – 45 min) before collecting samples.

6.2.3 **Wind Condition**

Due to the large number of the experimental units (48 plots), the weather station (Figure 3-1, described in Chapter 2) was installed in the middle of the grove. During the spray time, wind velocity and direction were measured at 10.0 and 4.0 m heights based on 1-Hz frequency. The data was transferred into a laptop computer, daily.

6.2.4 **Data Analysis**

Samples were kept in the refrigerator while waiting to be analyzed. They were analyzed by replication using fluorometric analysis (the same procedure applied in the open-area data analysis, section 5.1.8). However, at this test, a fluorometer model

10-AU (Turner Design, Inc., Sunnyvale, Calif.) was used to read the fluorescence concentrations (Fluors) in the sample solution. The fluorometer reads the Fluors in µg/L (ppb) unit, directly. It was calibrated with a known concentration of a standard solution made of stock solution. Based on the expected tracer concentration on each sample, different volumes of deionized water (DI) were used to wash the tracer from leaves. Two samples (about 10 ml) of the liquid of each washed-target were taken and two readings were recorded for each sample. Some samples of high concentration were diluted with DI water to bring their tracer concentration to a readable range.

A comparable tracer concentration (Dep_{comp}) (µg/cm^2) for all samples was calculated using Equation 5-2.

$$Dep_{comp} = \frac{Fluors \times w \times d}{A \times 1000} \tag{5-2}$$

Where w, d, and A are the washing water volume (ml), dilution factor, and the average leaf area (cm^2), respectively.

After washing the tracer out of the leaves of each sample, they were dried with paper towels and the total area of one-side of the them was measured using an area meter (Delta-T Devices, England) (Larbi and Salyani, 2012). The deposition readings were corrected by subtracting the deposition collected from blank (unsprayed) samples. The deposition readings were normalized based on the actual travel speed (2 km/h nominal), dye concentrations in the tank samples, and the nozzle flow rates. Final deposition values were statistically analyzed using SAS 9.2 software (SAS Inc.).

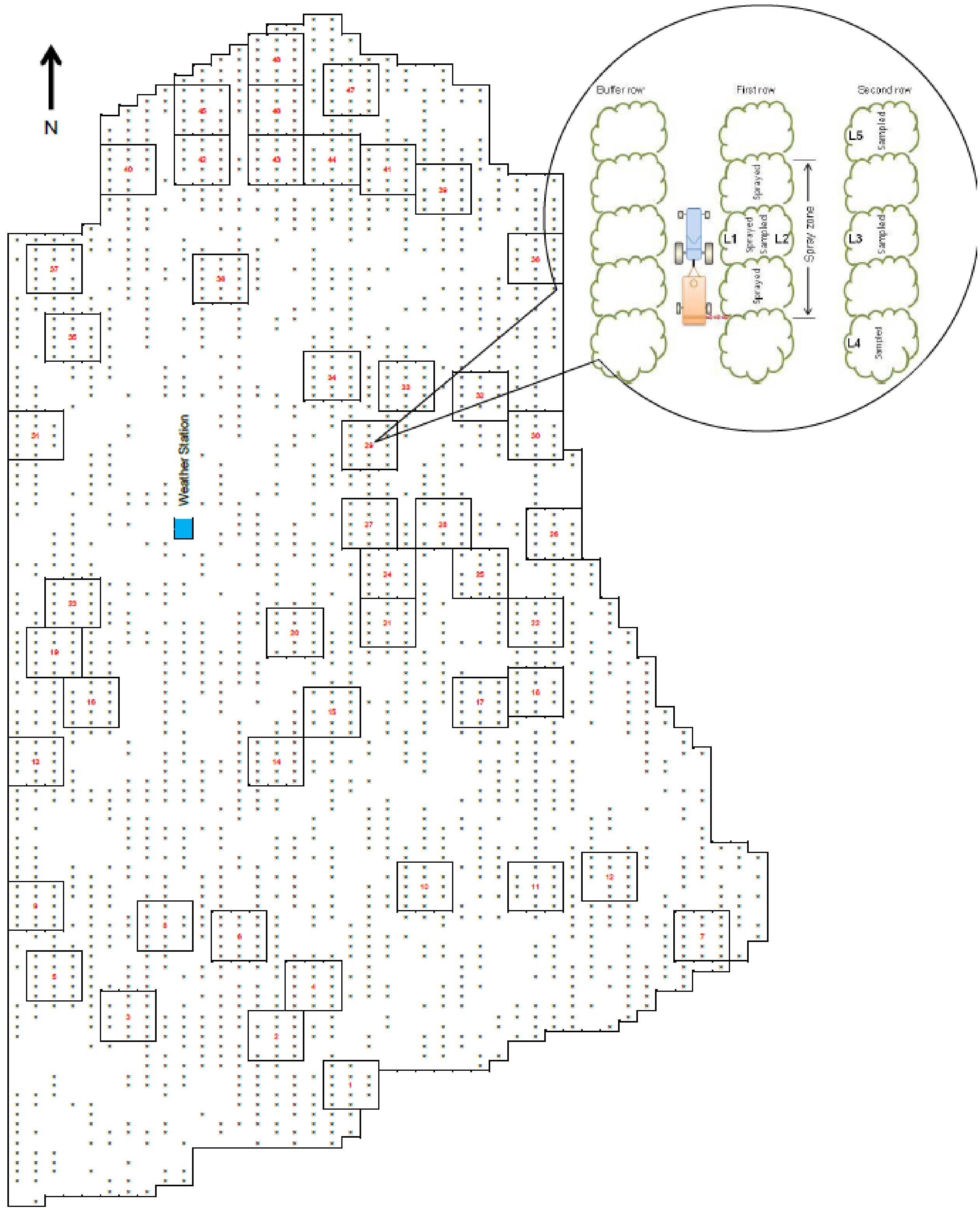

Figure 6-1. Sketch of the field experiment showing tree locations (dots), treatment plots (rectangles), and the sampling locations (L1 – L5).

Treatment means, coefficient of variation (CV), and means ratio were used to compare among the deposition at different treatment combinations. A regression analysis was used to establish any relationship between the wind conditions and the deposition variability among different treatments.

The way of relating wind effects to the deposition variability was made by calculating the x- or y-axis components of wind and finding the relationship between them and the deposition through a regression analysis.

Based on the recorded wind conditions, winds were named either as Parallel wind or Crosswind for those moved relatively parallel and perpendicular to the sprayer traveling line, respectively. Wind did not come exactly parallel or perpendicular to the sprayer traveling line. However, only treatments that have a wind direction within ± 45° (315° to 45° for the parallel and 45° to 135° for the crosswind) from the prevailing average of each group was included in the category. The x-axis and y-axis component of the wind in each category were used as parallel and crosswinds, respectively.

During the test, ambient wind moved mostly from the northeast direction. Also, the tree rows were moved from north to south. Therefore, for the same prevailing wind direction (say 45°), parallel wind that moved from the north was named “Headwind” when the sprayer traveled to the north (Figure 6-2). For the same sprayer traveling direction, the crosswind moved from east was called “Upwind” because the deposition was collected from the right-hand side of the sprayer operator, only. Changing the travel direction of the sprayer to move south, the same wind moved from the north was called “Tailwind” and the crosswind moved from the east was called “Downwind.”

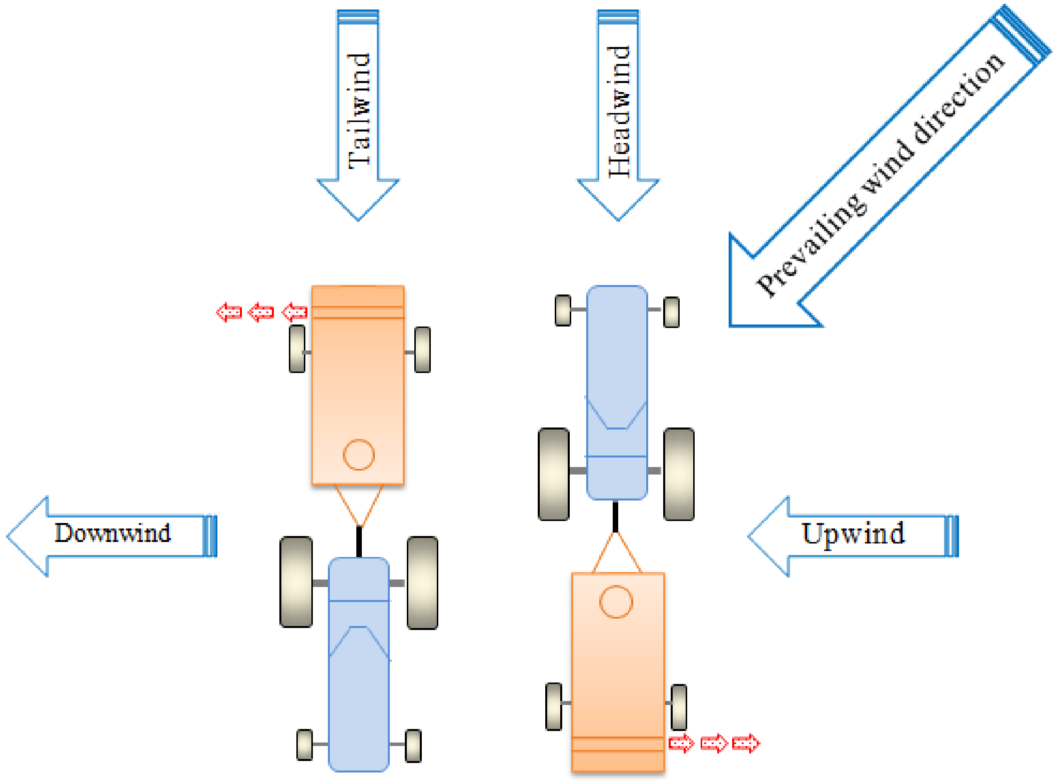

Figure 6-2. Sketch of the headwind, tailwind, upwind, and downwind categories based on the wind and sprayer travel directions.

Including the deposition collected at each location in the statistical analysis showed large differences among the locations. The deposition at L1, L2, L3, L4, and L5 was 398.8, 8.8, 5.7, 1.3, and 1.5 ng/cm^2, respectively. These differences between the location L1 and the others could mask the significant differences among the other locations. At the same time wind effect on the deposition at location, L1 may not be significant. Therefore, the data of location L1 was excluded from the comparison.

6.3 Results and Discussion

6.3.1 Wind Condition

Wind speed and direction recorded during each replication for each nozzle are shown in Table 6-1. Wind conditions during the tests changed within small ranges of speed and direction. At the same time, there was a lack of the repeatability of these conditions at different spray treatments. Those limitations might affect establishing strong relationships between the deposition variability and the wind conditions.

Table 6-1. Wind condition during the experiment conduction.

Reps.	Lilac nozzle				Blue nozzle			
	10.0 m		4.0 m		10.0 m		4.0 m	
	m/s	deg.	m/s	deg.	m/s	deg.	m/s	deg.
R1	4.40	3	2.87	359	2.14	73	0.86	61
R2	2.76	61	1.29	47	2.58	74	1.69	44
R3	5.07	66	2.57	67	2.92	84	1.38	89
R4	4.24	78	2.03	71	3.46	90	1.76	88
R5	4.08	73	2.01	69	3.55	74	1.68	70
R6	4.37	66	2.30	73	3.24	89	1.57	83

6.3.2 **Spray Parameters Effect**

Figure 6-3 shows the deposition resulting from using Blue and Lilac nozzles at fast and slow speeds. Using the Blue nozzle resulted in significantly higher deposition (5.7 ng/cm^2) than the deposition (4.0 ng/cm^2) of the Lilac nozzle (t-test, p=0.036). At the same time, changing the travel direction differentiated the deposition of both nozzles. For the Blue nozzle, the headwind direction resulted in significantly less deposition (3.8 ng/ cm^2) than the tailwind direction (7.6 ng/ cm^2). Similar trends and differences were found at the Lilac nozzle. Both headwind and tailwind resulted in a deposition of, 2.6 and 5.4 ng/ cm^2), respectively. As an overall average, increasing the travel speed of the sprayer from slow (2 km/h) to fast (6 km/h) significantly reduced the deposition from 5.1 to 2.9 and 7.0 to 4.4 ng/cm^2 for the Lilac and the Blue nozzles, respectively. The trends of deposition reduction by changing the travel speed were similar for both nozzles. Within each nozzle, driving speed differentiated the deposition for both headwind and tailwind (Figure 6-4). Driving the sprayer faster deflects the air-jet more and hence, fewer droplets reach their targets, especially at farther distances, which could explain the reduction in the deposition at fast speed. In addition, driving slow means larger airflow will be discharged for each travel distance unit, which helps the air-jet to penetrate into the canopy, cross it to the other trees row, and hence, increase the deposition. At headwind direction, the wind will face the sprayer and add more deflection to the sprayer air-jet. However, at the tailwind, it could follow the sprayer and mitigate the travel effect. Thus, changing the sprayer travel speed or direction could change the deposition, especially at windy condition.

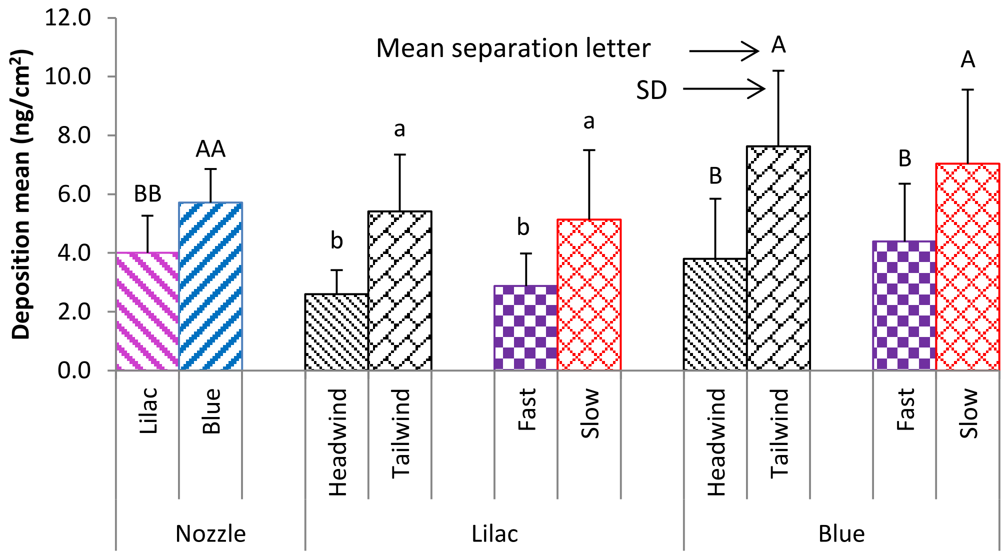

Figure 6-3. Deposition means of independent variables of the citrus grove test. Two neighboring bars with the same letter are not significantly different at 5% level.

Sampling from different locations away from the sprayer resulted in different depositions (Figure 6-5). The closer the sampling location to the sprayer is the more collected deposition. As overall averages, the deposition collected at the L2, L3, L4, and L5 was 7.5, 4.2, 2.0, and 2.3 ng/cm^2 for the Lilac and 11.1, 8.2, 1.8, and 1.8 ng/cm^2 for the Blue nozzles, respectively. However, driving direction (headwind or tailwind)

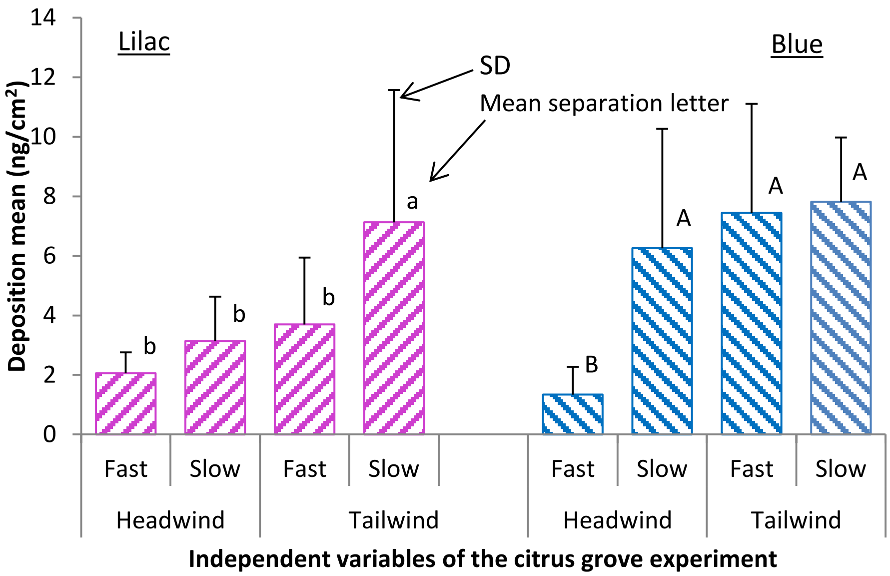

Figure 6-4. Effect of travel direction and travel speed on the deposition of each nozzle. Within each nozzle, bars with the same letter are not significantly different at 5% level.

differentiated the deposition within each location. The deposition collected at L4 and L5 was lower than that collected at the L2 and L3 locations. The locations L4 and L5 were already outside the spray zone and the spray cloud cannot reach them, directly. The location of L5 is always to the front of the spray zone while L4 located to the rear of the spray zone. Thus, from Figure 6-5, moving from L4 to L5, headwind tended to reduce the deposition. However, tailwind reversed the trend and significantly increased the collected deposition for both nozzles. The headwind stopped the spray cloud from reaching L5 while the tailwind moved more cloud towards the L5 and, hence more deposition. If the wind condition is still the same during the spray, the difference in the deposition between the two locations (L4 and L5) might not be evident however, due to the high variability in the wind condition; these locations will have different depositions.

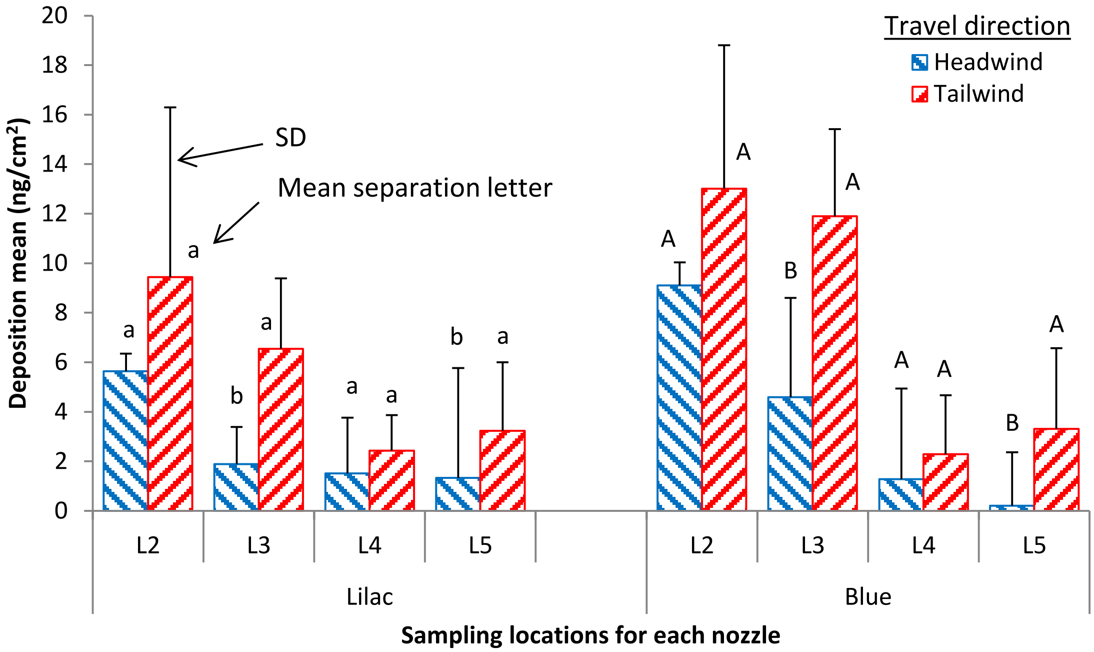

Figure 6-5. Mean spray deposition at different locations from the sprayer for Lilac (left) and Blue (right) nozzles. Within each nozzle and location, two neighboring bars with the same letter are not significantly different at 5% level.

6.3.3 **Crosswind Effect**

The crosswind was considered as the x-axis component of the wind (wind speed × sine of wind direction angle). It included the wind moved within a direction angle of 45° to 135° from the North, only. However, since most of the wind came from a direction extended from north to east, the two driving directions of the sprayer, south north, and north south were named as Headwind and Tailwind, respectively. In addition, due to the difference in the deposition between the Blue and Lilac nozzles, the relationship between the wind effect and the deposition of each nozzle was examined, separately.

For both nozzles, generally, increasing the crosswind increased the deposition collected at the second raw downwind and reduced it upwind. However, the regression analysis showed significant relationships between the deposition and the wind speed for some treatments, only. In addition, the coefficient of determination, R^2 has low values.

Figure 6-6 shows a reduction in the deposition at headwind direction (south north) by increasing the wind speed. Examining the relationship for each location, separately improved the R^2 values. Figure 6-7 shows the effect of the crosswind on the deposition at L5 located at the second row. At this location, changes in the deposition were significantly correlated with changes in the wind speed. Increased the wind speed reduced the deposition at headwind targets. Similar results were recorded at the L4 location. At slow speed, only L3 and L5 showed reductions in the deposition as the wind speed increased. However, the regression relationship was significant at the L5, only (Figure 6-8). The crosswind reduced the deposition on the L5 under both traveling speeds. However, the slopes of the reduction regression lines were different. For instance, for each 1.0 m/s increase in the wind speed, a deposition reduction about 0.3 and 1.6 ng/cm^2 could happen at the slow and fast travel speeds, respectively. This could be related to the volume of the delivered air-jet per distance unit. At slow speed, more volume was delivered, which could improve the air-jet movement and reduced the wind effects.

Measuring the wind effect downwind (changing the travel direction of the sprayer) showed a comparable results but at opposite trends to those obtained at the first direction. Increasing wind speed resulted in more deposition on targets downwind. Figure 6-9 shows an increase in the deposition collected at L5, downwind, by increasing the wind speed. The relationship between the wind speed and the deposition was not significant at the 5% level of significance. Similar result was recorded at the location L4 (Figure 6-10). Reducing the travel speed did not change the results at the L4 but the trend was not clear at the L5.

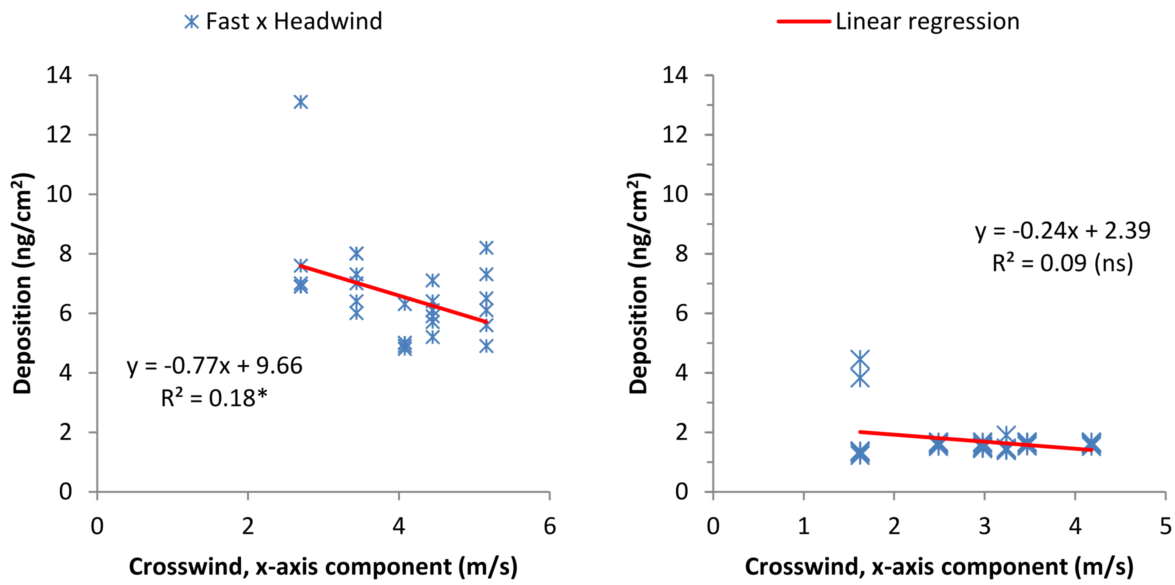

Figure 6-6. Crosswind effect on the deposition of the Lilac (left) and Blue (right) nozzles at the second row (L3, L4, and L5) upwind at fast travel. *= significant at 5% level. (ns)= non-significant at 5% level.

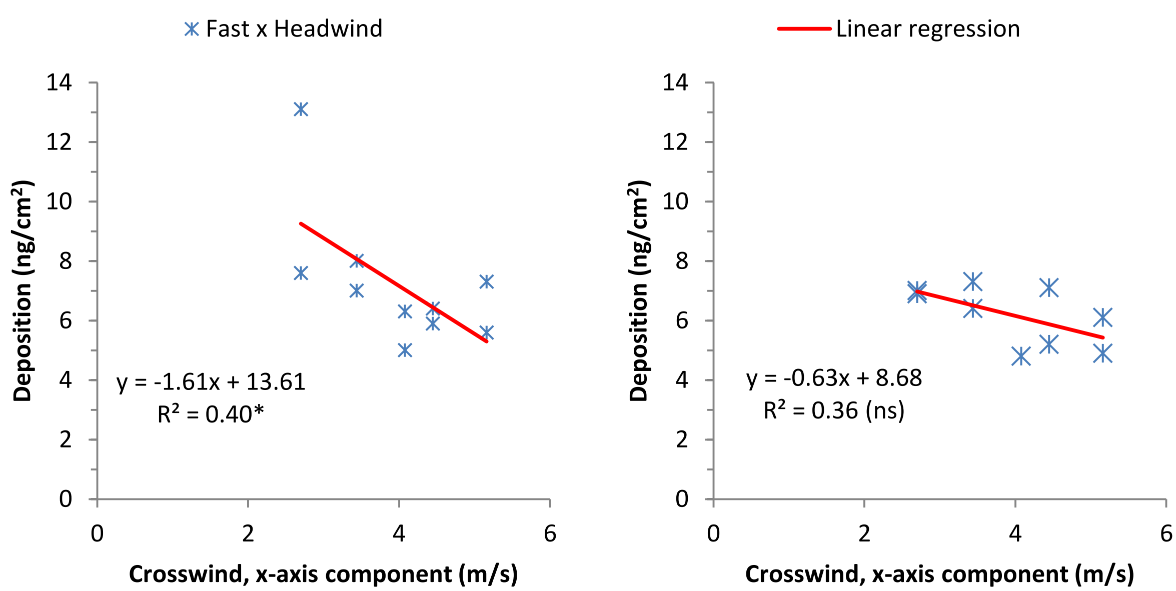

Figure 6-7. Crosswind effect on the deposition of the Lilac (left) and Blue (right) nozzles at the second row (L5) upwind at fast travel. *= significant at 5% level.

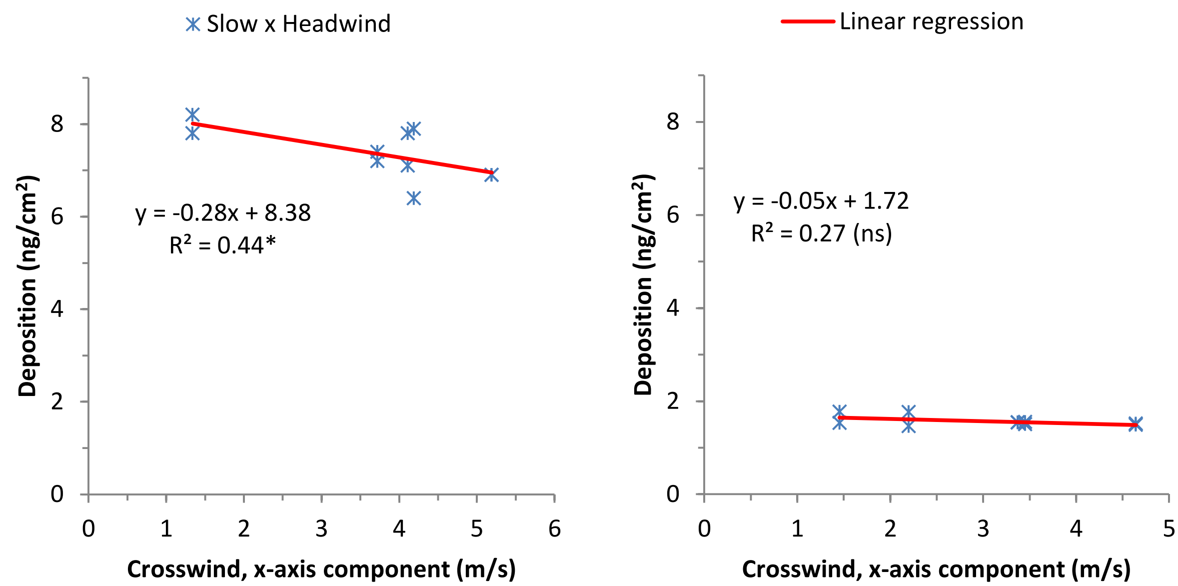

Figure 6-8. Crosswind effect on the deposition of the Lilac (left) and Blue (right) nozzles at the second row (L5) upwind at slow travel. *= significant at 5% level. (ns) = non-significant at level 5%.

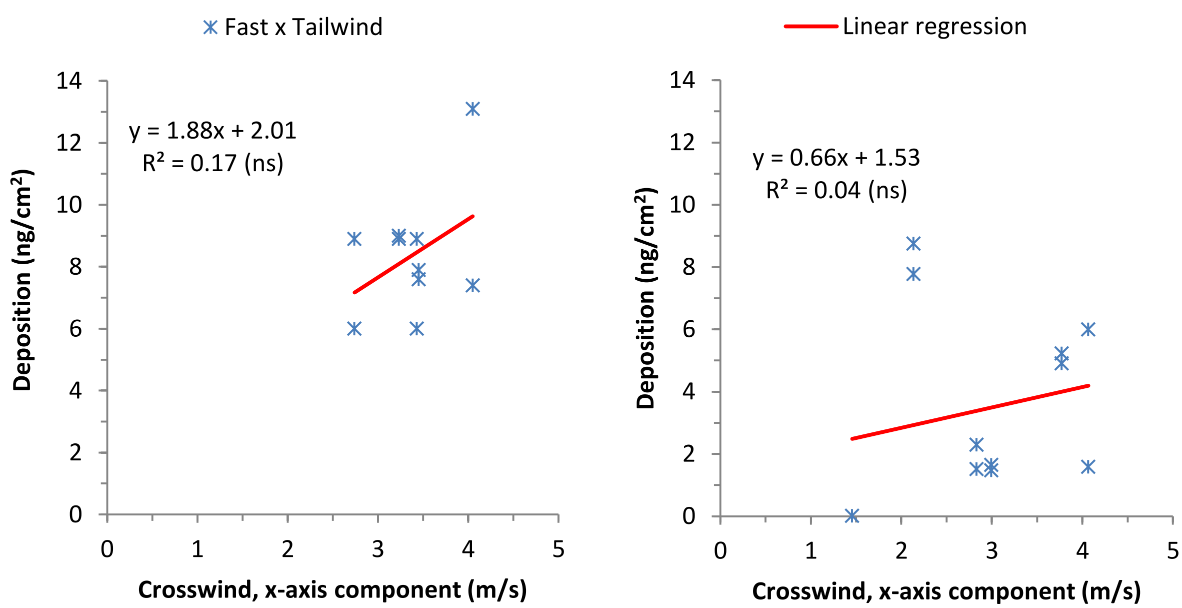

Figure 6-9. Crosswind effects on the Lilac (left) and Blue (right) nozzles deposition at the second row (L5) downwind at fast travel. (ns)= non-significant at 5% level.

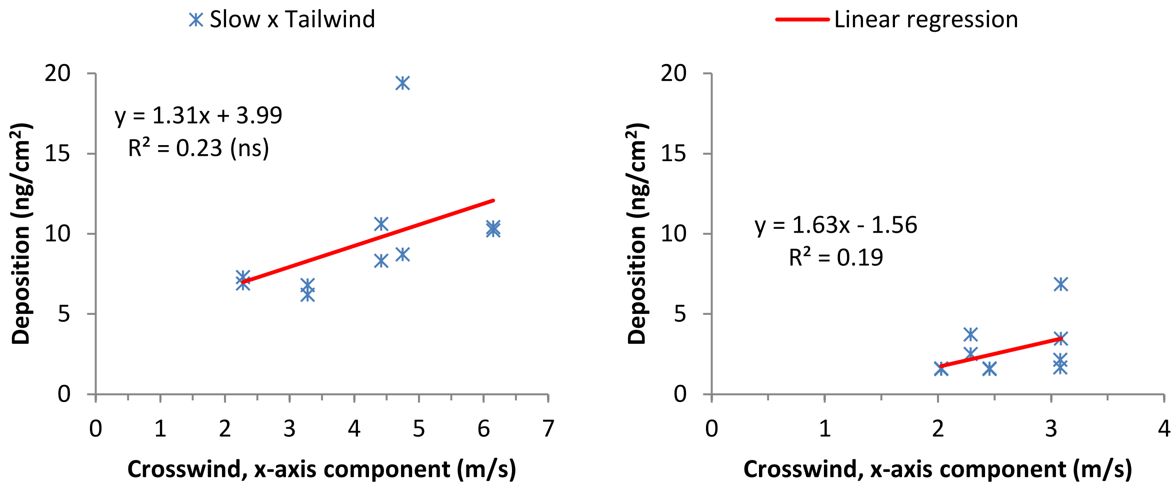

Figure 6-10. Crosswind effect on the deposition of the Lilac nozzle collected at the second row (L4) downwind at slow travel. (ns)= non-significant at 5% level.

For a deposition comparison between the upwind and downwind sides, the deposition ratios of L3/L2 in both sides were calculated (Figure 6-11). The ratio increased downwind while it decreased upwind. Changes in the ratio increased with increasing the wind velocity.

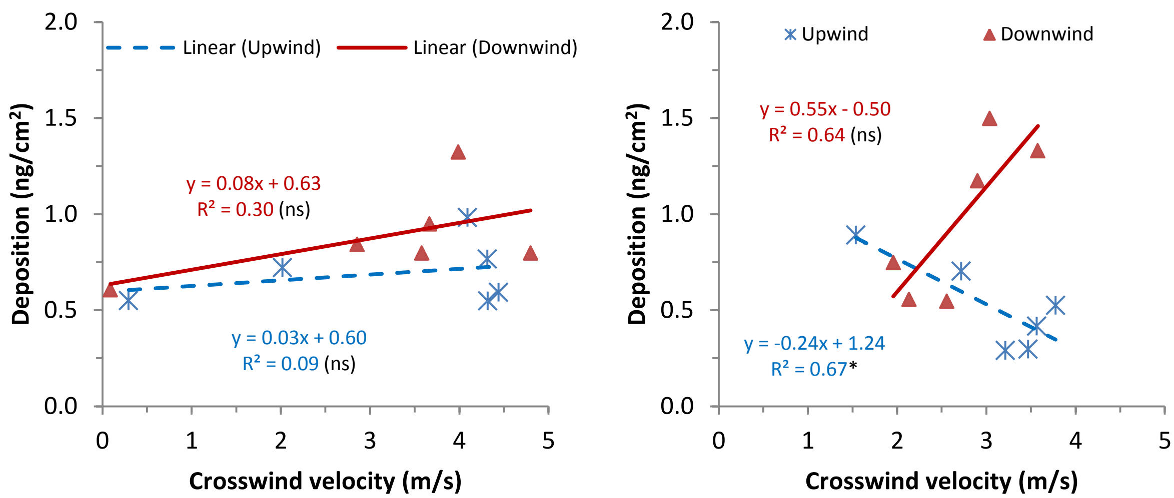

Figure 6-11. Crosswind effect on the deposition ratio (L3/L2) of the Lilac (left) and Blue (right) nozzles collected at the upwind and downwind. *= significant at 5% level. (ns) = non-significant at level 5%.

The relationships between the deposition variability and the wind condition, although they were relatively weak (low coefficient of determination, R^2), they give an indication about the trends of the wind effects on spray deposition in citrus.

6.3.4 **Parallel Wind Effect**

There was a lack of repeatability (two times only) of wind coming parallel to the sprayer direction (north south). In addition, these winds recorded at two different travel speeds for each direction. Therefore, the relationship between the deposition and the wind condition was not established.

6.3.5 **Deposition Variability**

The results showed clear differences in the deposition among the five locations around the sprayer due to the wind effects. Assuming the wind conditions will be similar for at least the spray time, deposition will be always high at downwind and low at upwind for each run. In other words, the crosswind will vary the deposition between the second rows to the right and left of the sprayer. Thus, there will be always unbalanced depositions at two tree rows. However, wind speed and direction change, rapidly. Thus, they will change the trend of the variability in the deposition and add more complexity to the situation.

The following conclusions could be drawn from the field experiment:

1. For the test variables (nozzle type, travel speed, travel direction, and sampling location), generally, there were comparable trends in the open field and citrus grove experiments.

2. Changing the sprayer travel speed from 2 to 6 km/h increased the overall deposition mean by 12% (due to decreased runoff from the leaf surfaces at locations close to the sprayer) when all sampling locations were included in the mean calculation. However, excluding the data pertinent to locations nearest to the sprayer (L1) reversed the trend and resulted in a deposition reduction of 40%.

3. The mean deposition collected when travelling upwind was about 50% of the deposition collected at travelling downwind. Increasing the crosswind velocity increased the deposition difference between the two sides. However, it was not possible to establish a clear relationship between the wind condition and the deposition variability. Increasing the number of replications might be helpful in establishing clearer trends.

4. Increasing the sprayer travel speed from 2 to 6 m/s reduced the overall deposition mean by 40%. However, the reduction was higher for the headwind than the tailwind.

CHAPTER 7
OVERALL CONCLUSION AND FUTURE WORK

7.1 Conclusion

Ambient wind conditions within citrus groves were significantly different from those recorded outside the groves. The wind changed rapidly with high variability in short period. Within one minute, wind condition could change from no wind to higher wind speeds at which spraying might be objectionable. These changes are normally masked by long averaging intervals typically used in most weather stations.

In laboratory test, wind reduced the velocity of an air-jet by about 20% and deflected its direction by about 12 cm, measured at 85 cm from the air outlet. Increasing the wind speed resulted in more reduction in the air-jet velocity and its deflection. The distortion of the air-jet due to the ambient wind reduced the deposition by 34%.

Under field conditions, crosswind, headwind, and tailwind affected spray deposition; however, the effect was different at various sampling locations. In the open-area, the deposition collected downwind was about one to three times the amount collected upwind. In the citrus grove, the deposition downwind was still twice as much as the amount of spray deposited upwind. In both test sites, the ambient wind significantly reduced the overall deposition. However, due to the high variability of wind speed and direction, it was not possible to establish a clear relationship between wind conditions and spray deposition. Derivation of these relationships will require more replications under each wind condition, which was not available during this test.

Finally, spraying under windy conditions resulted in a non-uniform deposition for the two sides of the sprayer. Travel direction of the sprayer interacted with the wind, which in turn changed the deposition trend further. The variability in the deposition could affect the efficacy of the pesticides in some applications.

7.2 Future Work

Studying wind conditions requires many sites and replications in order to provide reliable trends. The use of an off-site weather station such as FAWN may not be enough to predict wind conditions within grove; therefore, multiple weather stations should be used if available. In spray studies, wind conditions need to be measured as closely as possible to the spray area to capture any spatial variability or momentary changes in wind conditions that could vary the deposition. The variability related to some variables such as nozzle type that are already known to have different spray characteristics could mask significant differences for other test variables. Therefore, they need to be tested separately. Larger number of replications with fewer variables is required to study the wind effect on deposition because there is always lack of repeatability in the wind condition. In addition, if leaves will be used as deposition targets, more blank samples from each test plot need to be taken in order to more reliably quantify background deposit according to the age, shape, and projecting angle of the leaves.

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BIOGRAPHICAL SKETCH

Ahmed was born in a village in the western part of Iraq. He grew up within a farming family, which made him involved in the hard work of Agriculture. From that, Ahmed's experience and his passion to the Agricultural Machinery that could ease the work were started. Ahmed attended the University of Bagdad to study for his undergraduate degree in 1987. He graduated in 1992 with a bachelor of science in Agricultural Mechanization with a rank of three over the whole College. Ahmed received the Ministry of Higher Education and Scientific Research award, designed for the third-ranked student.

Ahmed got a position as an agricultural engineer in IPA Center for Agricultural Researches at 1994. He was nominated by his company to study for his master in 1997. He got his master degree in Agricultural Machinery from the University of Bagdad in 2000. During his employment as agricultural engineer working in a research center, Ahmed gained very good experience of designing and conducting experiments. In addition, he led or participated in different teams of his company to import, evaluate, or maintain agricultural machinery.

In 2007, Ahmed got a scholarship from the Ministry of Higher Education and Scientific Research in Iraq to study for his PhD degree at the University of Florida. During his English study at UF/ English Language Institute, Ahmed was one of two students who awarded a scholarship to study for one semester free in the institute. Ahmed started his PhD program in 2009. He received his PhD in Spray Application Technology from the University of Florida in 2013. Ahmed lives with his wife, four daughters, and son.