Variability of wind conditions in citrus groves compared with those recorded outside

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Abstract: Wind velocity and direction, which are normally reported at certain time intervals, fluctuate substantially within a short time frame. These fluctuations may have a significant effect on spray deposition of air-assisted sprayers used in citrus production. Wind measurements are usually made inside or outside a grove at about 10 m height but the latter may not accurately represent the wind conditions within the grove. The objective of this study 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 at different heights. Within the grove, wind velocity and direction data were collected at 10.0, 3.6, 3.0, 2.4, 1.8, 1.2, and 0.6 m above the ground at 1-s interval. For the same period, FAWN data were available at a minimum of 15-min interval. Results of the 10-m height measurements showed good correlation between wind conditions recorded outside grove and those collected within the grove (r = 0.69 and 0.94 for wind velocity and direction, respectively). However, average wind velocity and direction at both sites were significantly different (p = 0.05). Within the grove, wind velocities of 1.5 m/s or less, recorded at 10 m height, showed almost zero wind velocity at lower heights. Within the grove, maximum wind velocities recorded at 3.6 – 0.6 m amounted to only 59% – 20% of wind velocity recorded at 10 m, respectively. Averaging wind velocity over 15-min interval reduced the wind variability of 1-s interval by 90%. For field characteristics similar to those described in this study, wind conditions recorded at 10 m height outside grove cannot reliably represent wind conditions inside grove, particularly within the canopy height.

Keywords: FAWN, spraying conditions, wind direction, wind measurement site, wind sensor, wind velocity

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1 Introduction

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 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., 2004; Salyani et al., 2007). The air-jet transfers spray droplets onto the canopy and helps them to penetrate within the canopy. Droplets 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).

It is advised to avoid spray when wind speed is greater than 4.5 m/s (Salyani, 2013) and preferred to spray when wind is calm. However, specifying the best wind speed range for spray is still under study. Due to the absence of suitable wind conditions during most applications and the urgency to control a pest outbreak, sprays are often applied at relatively windy conditions (Reichard et al., 1979). Wind could reduce the air-jet

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velocity or shift its direction (Fox et al., 1985). The distortion of the air-jet may result in non-uniform spray deposition and poor biological efficacy. The portion of the applied pesticide that does not reach the intended target not only results in wastage of the material but also could be an environmental hazard. Therefore, pesticide losses should be minimized as much as possible.

1.1 Wind effect

In a study of the effects of wind conditions on deposition and drift from aerial applications, Bird (1996) and Fritz (2006) found that wind velocity is the most influential factor on drift. Traveling distance of drifted droplets depends directly on the wind velocity. Fritz (2004) also found wind velocity as a significant factor affecting spray ground deposition and its airborne concentration. Furthermore, Thistle et al. (1998) and Salyani (2000) found that wind direction is the most important factor affecting spray efficiency. Strong winds could move the droplets out of the application site or redirect them onto very sensitive areas or objects. 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 experimental field, as co-variables.

Results of a study conducted by 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 ten times after 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%.

1.2 Wind variability

Wind conditions within a grove usually differ from those outside the grove to some extent. These differences are more evident within the canopy height. Fons (1940) studied the wind velocity and direction at different heights within open grassland, moderately dense ponderosa pine, and brush areas. The vegetative coverage on these sites was approximately 0.15, 21, and 1.40 m above the ground, respectively. The results showed a linear relationship between any two measuring heights. However, different heights had different linear slopes and intercepts. These parameters were correlated with the lower measuring height. Baynton et al. (1965) studied metrological conditions above and within the canopy structure of a tropical forest. They found that wind velocity within the canopy, based on half-hour averages, reduced to about 1%–5% of the velocity recorded at 61 m above the ground. Wind direction averages, recorded at the 61- and 45-m heights at two locations 1100 m apart, were in good agreement (R^2 = 0.95); however, they changed randomly within the canopy height. Renaud et al. (2011) 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).

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 15-min interval. Studying wind conditions at different levels within the canopy height might help the applicator to understand deposition variability on canopy and improve spray efficiency. Furthermore, it should be mentioned that although weather conditions are usually measured at 2-m and 10-m heights (ASABE Standards, 2009b) outside the grove they may not reliably represent the conditions inside the grove, which affect the spray deposition. However, in the absence of local stations, wind conditions collected at far distances are normally used by many growers. 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.

Therefore, work reported in this study is a part of a continued research to understand the effect of ambient wind on the spray deposition within citrus groves. Specific objectives of this study are 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.

2 Materials and methods

2.1 Data collection

A portable weather station was set up inside a citrus grove in Lake Alfred, Florida (N 28º 06' 18.93", W 81º 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. Also, 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 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 $m \cdot s^{-1}$. The upper height was fixed at 10 m above the ground for all measurements. 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. 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 portable 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. Both systems are commonly used in wind speed measurements (ASABE Standards, 2009a). In the absence of two identical systems for this study, the measurements of the two systems were compared and the data of the cup anemometer were normalized based on their differences. The ultrasonic sensor (model 425A, Vaisala, Helsinki, Finland) had an accuracy of ±0.14 m/s and ±2º for wind velocity and direction with almost zero wind velocity threshold. Wind speed and direction were collected on both stations at the same height (10 m) for 7 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 portable station sensor, recorded in the grove at 10 m height. The same procedure was done to the wind direction sensors.

2.2 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 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 variance (CV), maximum value (Max), minimum value (Min), and the 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 following equations:

$$SD = (-2\ Ln\ (R))^{0.5} \qquad (1)\ \text{(Mori, 1986)}$$

where,

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

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

$Ca = n^{-1} \sum \cos D_i$

$D_i = i^{th}\ angle\ of\ wind\ direction$

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-min 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- min 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 $m{\cdot}s^{-1}$ 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 $m{\cdot}s^{-1}$ was used as the 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 student's *t*-test at 5% level of significance.

3 Results and discussion

3.1 Grove wind data correction

Figure 1 shows the comparative 15-min interval wind velocity and direction data recorded by the portable 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 portable 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 portable (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.

$$y = 0.95x + 0.33 \quad (2)$$

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

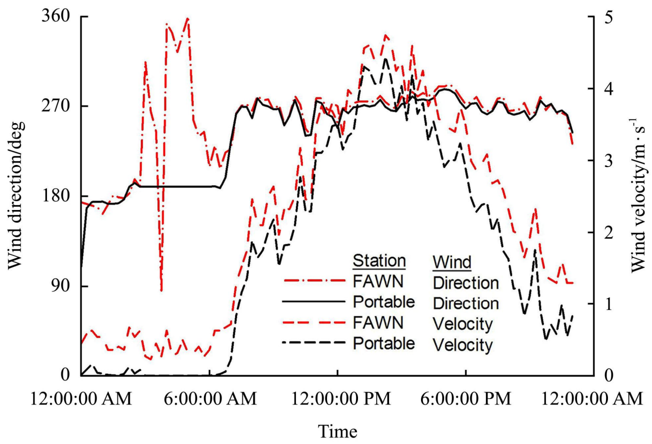

Figure 1 Comparison between wind velocity (dotted lines) and direction (solid lines) recorded by the FAWN and portable stations at 10-m height (15-min interval)

3.2 GROVE and FAWN comparison

3.2.1 Wind velocity

Figure 2 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. Therefore, the use of FAWN weather data to characterize the weather condition inside groves that have 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, cup anemometer has a static friction and inertia effect while 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 recordings, maximum wind velocities of the GROVE and FAWN stations were, respectively, 9.77 and 8.54 m/s, at the same time on a certain day. This indicates that wind velocity recorded at one station was not necessarily the same at the other station; however, general trends of wind velocities on both locations were comparable.

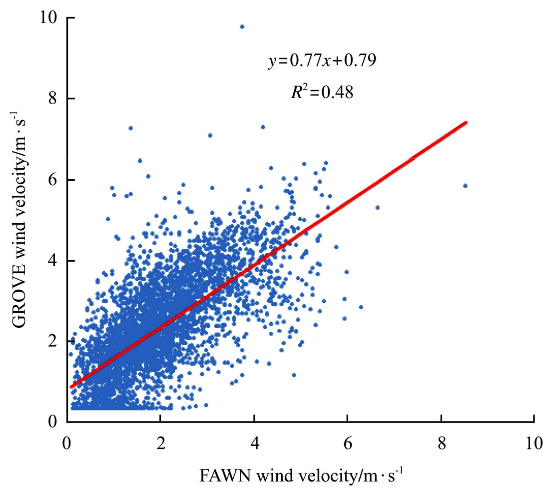

Figure 2 Relationship between GROVE and FAWN wind velocities

3.2.2 Wind direction

Over 6 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 the student's 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 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.

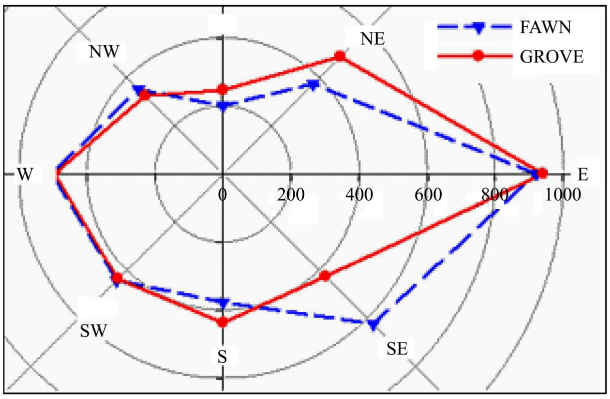

Figure 3 Relationship between GROVE and FAWN wind direction. The circles show the frequency of the measurements.

Table 1 shows the difference in wind direction recorded by the two stations at eight half quadrants. West (W) and east (E) half quadrants showed significantly lower differences between wind directions recorded by the two stations. The other half quadrants had higher direction differences and the mean difference between the two groups was 6.5°. This difference could come from the effects of the obstacles located at the north and south of the FAWN station. They could have less effect on the winds coming at east-west direction compared with winds from other directions. While the wind directions recorded at both stations were similar in some cases, they were different in other situations. This wide range of the differences between the directions of the two stations resulted in high variability of the measurements among all half quadrants. Therefore, the results indicate that wind direction could affect the difference between the readings of the two stations.

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

Differences	Wind direction (half-quadrant)							
	N	NE	E	SE	S	SW	W	NW
Mean/(°)	27	24	18	25	23	23	18	25
SD/(°)	34	24	22	26	28	23	25	36
CV/%	126	103	124	101	121	100	139	145
n	158	395	919	626	385	456	504	352

Note: SD, CV, and n = standard deviation, coefficient of variance, and the number of observations in each direction.

3.2.3 Wind velocity difference verses 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 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.

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.

Table 2 Wind velocity differences between GROVE and FAWN in relation to the wind direction

Differences	Wind direction (half-quadrant)							
	N	NE	E	SE	S	SW	W	NW
Mean/m s^{-1}	-0.18	0.10	-0.07	-0.32	-1.06	-0.77	-0.38	-0.35
SD/m s^{-1}	0.73	0.74	0.80	0.93	0.96	0.85	0.95	0.70
CV/%	406	721	1212	292	90	110	250	202
n	190	421	945	655	404	464	530	384

Note: SD, CV, and n = standard deviation, coefficient of variance, and the number of observations within each half quadrant.

3.3 Within the GROVE comparisons

Figure 4 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.

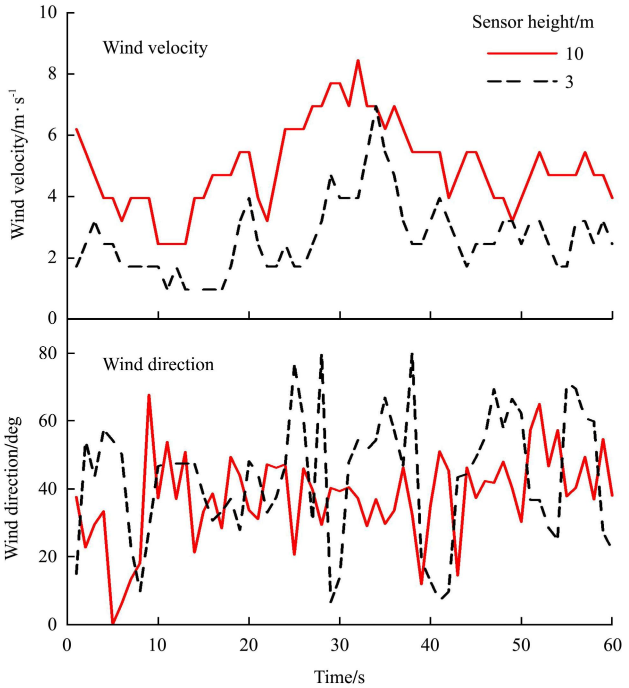

Figure 4 Typical trends of wind velocity (top) and direction (bottom) for a one-min recording period

3.3.1 Measurement height effect

Figure 5 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. (2011). 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). 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 360º. 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°.

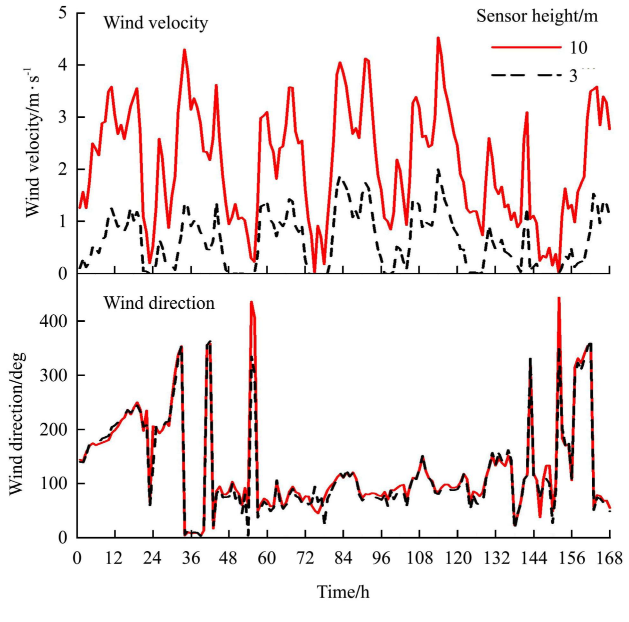

Figure 5 Relationship between wind velocities (top) and directions (bottom) recorded at 10 and 3.6 m height

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 it 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 6).

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.

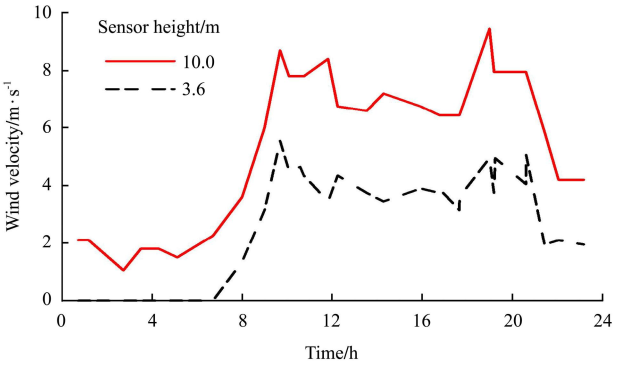

Figure 6 Maximum wind velocities at 10.0 and 3.6 m heights

3.3.2 Comparison of recording intervals

Figure 7 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 – 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 – 4.4 m/s (CV of 3%). 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.

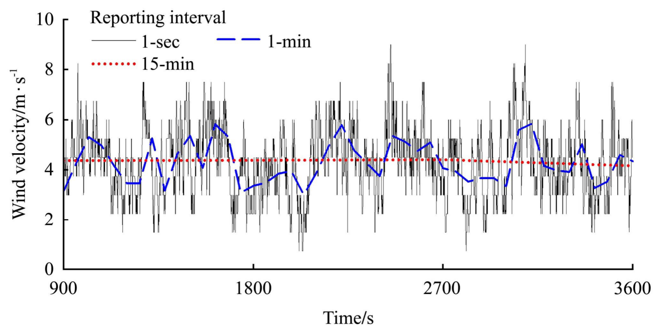

Figure 7 Variability of wind velocity at different measuring intervals

3.4 Prediction of wind velocity

3.4.1 Above the canopy height

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

$$wv_G = 0.77 \times wv_F + 0.79 \quad (3)$$

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

Equation (3) utilizes wind velocity recorded at 10 m height outside groves to estimate wind velocity above the canopy. The equation has a coefficient of determination (R^2) of 0.48. The low coefficient 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.

Within the canopy height

Figure 8 shows the established relationships of the acceptable data 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.

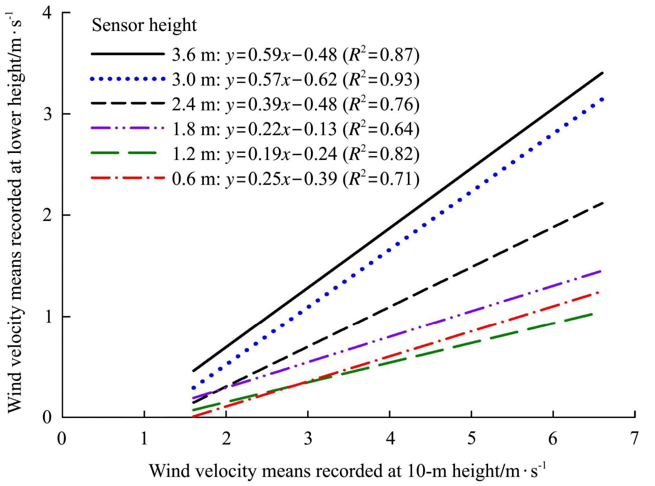

Figure 8 Relationships between wind velocity averages at different heights within the grove at 15-min interval

Figure 9 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 resulted in a corresponding increase in the velocity recorded at each lower height within the canopy level. However, the increase in wind velocity diminished as the measurement height decreased. 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 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.

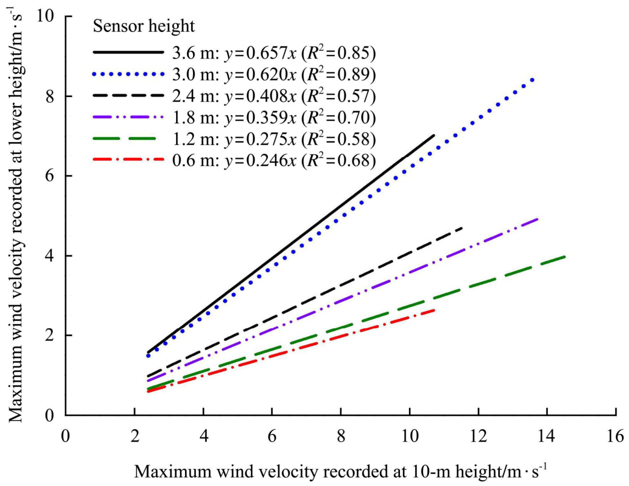

Figure 9 Relationships between wind velocity maximums at different heights

3.4.2 Wind velocity ratios

Figure 10 shows the ratios 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

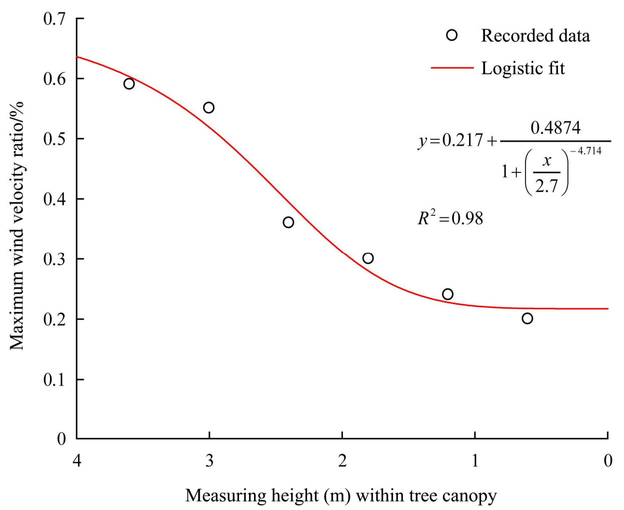

Figure 10 The change in maximum wind velocity ratio within the canopy height

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.

4 Conclusions

- For field characteristics similar to those described in this study, wind conditions recorded at 10 m height outside grove cannot reliably represent wind conditions inside grove, particularly within the canopy height.
- Tree canopies reduced wind velocity significantly, and the reduction was dependent on the measurement height.
- Wind velocity at the canopy level may be estimated from the measurement made at 10 m height inside grove.
- Wind variability affecting spray deposition could be masked by long averaging intervals.

Based on the study outcomes, it is recommended to combine a variability index such as SD or CV with the wind conditions averages reported for long periods. It will be more beneficial if wind conditions within groves at different distances from the FAWN stations were included. For field experiments that are relatively affected by ambient wind changes, wind conditions need to be collected as close as possible to the test area.

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