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Spatial Variability of Leaf Wetness Duration in Citrus Canopies

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Leaf wetness duration (LWD) is a key parameter in some disease warning systems and as an input to biological modeling of infection of many plant diseases in crops. The main objective of this study was to determine the spatial heterogeneity of LWD within citrus canopies during summer and winter conditions. The spatial variability of LWD was evaluated in citrus trees in central Florida at 12 canopy positions during Aug. 2008 and Feb. 2009. The analysis of LWD measurements revealed statistical heterogeneity among sensor heights and horizontal positions. LWD was significantly higher ($P < 0.0001$) at the top canopy compared to the middle and bottom positions during rainy days and no-rain days. The differences in mean daily LWD between top and bottom canopy during a 31-d period of time in the summer were 2.9 and 2.5 h during no-rain and rain days, respectively. The difference in mean daily LWD during a 30-d period in the winter with no-rain days was 2.6 h. The comparison by linear regression analysis between sensors within the canopy and a sensor installed at 30 cm (0.98 ft) over turf grass in a nearby Florida Automated Weather Network (FAWN) station showed that the station sensor provides accurate estimates of LWD at the top of the canopy. These findings accentuate the importance of accounting for the impact of spatial heterogeneity when LWD is used as input to disease-warning systems.

The period of time during which free water is present on the outer surfaces of crop plants has been defined as leaf wetness duration (LWD). It depends on the properties of surfaces as well as the atmospheric conditions and its occurrence is linked to the occurrence of dew, rainfall, fog and irrigation (Klemm et al., 2002). Unfortunately, regardless of its importance in agriculture and the large amount of research on LWD, it is considered a non-standard meteorological parameter and there is no accepted standard protocol to measure or estimate it (Magarey, 1999). LWD and air temperature are two of the most important micrometeorological parameters influencing the development of many foliar and fruit diseases (Agrios, 2005; Gillespie and Sentelhas, 2008). Therefore, LWD is a key parameter in decision support systems as an input to biological modeling of infection of many important fungal diseases in crops (Huber and Gillespie, 1992; Sentelhas et al., 2006).

LWD is a spatially heterogeneous weather input to plant disease warning systems because it responds to subtle changes in atmospheric conditions such as relative humidity, wind speed, cloud cover, and the structure and characteristics of the crop canopy (Gleason et al., 2008; Sentelhas et al., 2004). Batzer et al. (2008) investigated the influence of the spatial variability of LWD within apple trees canopies on the performance of a warning system for sooty blotch and flyspeck (SBF). They concluded that when LWD measurements from several canopy positions were input into the SBF warning system, the timing of occurrence of a fungicide-spray threshold varied by as much as 30 d among canopy positions. Their results suggest that within-canopy LWD spatial variability affects the performance of disease warning systems.

Moreover, Sentelhas et al. (2005) and Santos et al. (2008) investigated the spatial variability of LWD within crop canopies and found patterns of variation. Santos et al. (2008) found that coffee plants showed the longest LWD in the lower portions of the canopy; banana plants had the longest LWD in the upper third of the canopy, whereas no difference was observed between the top and lower third of the canopy for the cotton crop. Furthermore, Sentelhas et al. (2005) found that the LWD was longer at the top in apple and maize plants, whereas for coffee plants and grapes cultivated in a hedgerow system, the average LWD did not differ between the top and inside canopy.

Citrus trees are susceptible to many plant pathogens capable of causing diseases. These diseases seriously impact the number and quality of marketable fruit causing important economic losses. Major citrus diseases currently present in Florida include blight, greasy spot, tristeza, Alternaria brown spot, Phytophthora induced diseases, melanose, canker, scab, postbloom fruit drop

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(PFD), and Huanglongbing also commonly called citrus greening (Spann et al., 2008).

Prediction models for Alternaria brown spot and postbloom fruit drop have been developed as disease control tools. The Alter-Rater model was developed for control of Alternaria brown spot, caused by *Alternaria alternata* Corda, which seriously reduces yields of tangerines and their hybrids in Florida. The Alter-Rater model predicts the need for fungicide applications based on daily cumulative points that are assigned on the basis of rainfall, LWD and temperature (Timmer et al., 2001). Bhatia et al. (2003) found that the Alter-Rater model resulted in fewer sprays compared to a calendar spray schedule and its use also results in better disease control.

In addition, a model for postbloom fruit drop, caused by *Colletotrichum acutatum* Nees, has been developed to assist growers in determining the need and timing of fungicides applications. The model predicts the percentage of the flowers that will be affected 4 days in the future based on the amount of inoculum along with the total rainfall and LWD for the last 5 d (Peres et al., 2004). Timmer et al. (1996) found that the model-based decisions on fungicide applications resulted in reduced disease, large increases in fruit production, and elimination of unnecessary sprays. Model predictions were accurate except when rain events were of short duration and tree canopies dried quickly.

Citrus plants are large shrubs or small trees where a wide range of leaf wetness variability may be expected throughout the canopy. Accurate LWD data are important inputs in these disease warning systems to ensure acceptable disease control with a reduction of input costs by optimizing the number of pesticide applications. Thus, a good understanding of the spatial heterogeneity of LWD within the canopy may be important to improve the performance of disease warning systems. The objectives of this research were to: 1) evaluate if LWD patterns vary within the canopies of typical citrus species cultivated in central Florida; 2) compare the spatial variability of LWD during summer and winter conditions; and 3) compare LWD patterns within citrus canopies with leaf wetness duration measured over turfgrass in a nearby Florida Automated Weather Network (FAWN) station.

Materials and Methods

Leaf wetness duration measurements. The experiment was located in the University of Florida Citrus Research and Education Center (UF-CREC) in Lake Alfred (28°06'N, 81°42'W). Lake Alfred is located in the central region of Florida and has a prevalent humid subtropical climate. LWS-L dielectric leaf wetness sensors (Decagon Devices, Inc., Pullman, WA) were used to estimate leaf surface wetness by measuring the dielectric constant of the sensor's upper surface. The sensor consists of 0.65 mm (0.0256 in) thick fiberglass and it mimics the thermodynamic and radiative properties of real leaves. The sensor output is a mV signal proportional to the dielectric constant of the measurement zone which is also proportional to the water amount on the sensor surface. Most applications that utilize leaf wetness estimates, such as disease warning systems or disease forecasting, require knowledge of the presence of free water on the surface but recording the exact amount of water on the surface is not necessary. The threshold logger reading for the LWD sensor to be considered wet is when ≥274 mV is recorded at 2.5 VDC excitation. Painting or calibration of individual sensors is not required. A test conducted in the laboratory successfully assessed the agreement between the output on the sensors and actual observations of leaf wetness. CR10X data loggers (Campbell Scientific Inc., Logan, UT) were used to scan measurements every 15 s that were averaged every 15 min. LWD was accumulated and summarized for every 12-h period from midnight to noon and noon to midnight.

Twelve LWS-L sensors were installed in each tree of the selected citrus species: grapefruit (*Citrus paradisi* Macf.) cv. Marsh Seedless, sweet orange [*Citrus* ×*sinensis* (L.) Osbeck] cv. Hamlin, and a tangerine (*Citrus reticulata* Blanco) hybrid cv. Fallglo. The selected trees were in close proximity to each other and with similar canopy structure and developmental stage. All the trees were planted around 1990 and are considered mature bearing trees. Sensors were placed at 0.6, 1.5, and 2.4 m (1.97, 4.92, and 7.87 ft) above the ground; each height representing the lower, middle and upper canopy, respectively. At each height, four sensors were placed at four horizontal positions approximately 0.6 m (1.97 ft) apart along an east–west transect as shown in Fig. 1. The sensors were placed in a northward facing position at an inclination of 45° to the horizontal (Sentelhas et al., 2004).

LWD was also monitored by two LWS-L sensors installed at a FAWN station located at the UF-CREC, about 50 m from the citrus crop test area. Sensors were installed at 0.30 m and 2.0 m (0.98 ft and 6.56 ft) above the ground over turf grass in a northward facing position at an inclination of 45° to the horizontal.

Data analysis. LWD observations were collected in Aug. 2008 and Feb. 2009 to represent summer and winter seasons, respectively. Summer daily observations (00–24 h) were partitioned into rain days and no-rain days. A day was defined as a rain day when measured rainfall during the 24-h period was ≥0.25 mm (0.01 inch). In Feb. 2009, the Pacific Ocean was in the La Niña phase (colder than normal ocean temperature along the equator in the eastern and central Pacific) which brings drier weather to the peninsula of Florida. Average La Niña rainfall is 30% to 60% less than normal. This La Niña event resulted in below-normal rainfall, and no day with rainfall ≥0.25 mm (0.01 inch) was reported during the winter data collection period of time. Therefore all days during the winter season were categorized as no-rain days.

Our main hypothesis was that all canopy positions had equivalent LWD. This hypothesis was evaluated using the Generalized Linear Mixed Model (GLMM) using the SAS Glimmix procedure (SAS Institute, Inc., Cary, NC). Height and horizontal positions represented the fixed effects. Species was considered as the random effect due to the lack of replication within species which prevented a valid statistical analysis to detect differences among species; but an analysis of variance (ANOVA) revealed that there were not statistical differences in LWD among trees. Responses on different days were assumed not to be independent and the autoregressive covariance structure was used to model the correlations between days. The least squares means (LSM) multiple comparison test which produces a t test for each fixed effect was used to compare the means between factors. We also hypothesized that potential differences in LWD would be less significant during rainy days than during no-rain days. The hypothesis that after a daytime rainfall event the LWD would be shortest at the top of the canopy, which is more exposed to wind and solar radiation, was also assessed. To test this hypothesis while eliminating the effect of dew, seven daytime rain events in which the rain occurred between 9 AM and 3 PM were analyzed. Finally, a linear regression analysis was conducted between the FAWN station sensors at 0.30 m and 2.0 m (0.98 ft and 6.56 ft) above turf grass and the sensors installed within the canopy of the three citrus species.

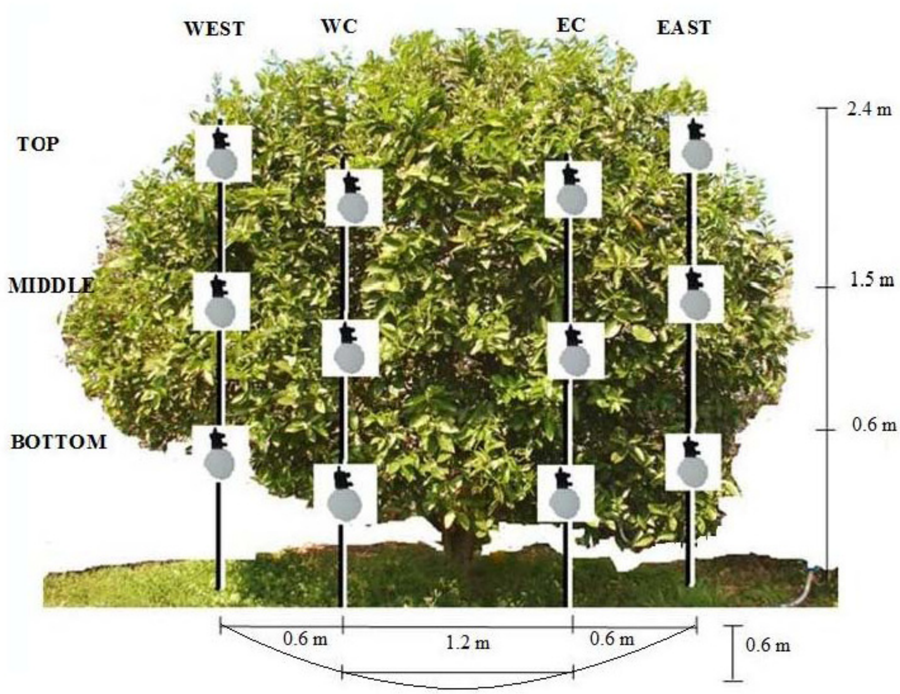

Fig. 1. Location of leaf wetness sensors in citrus canopies. Sensors were located at three heights: top, middle, and bottom; and four horizontal positions: west, west-central (WC), east-central (EC), and east.

Results and Discussion

Spatial variability of LWD within citrus canopies. The statistical analysis of the overall data revealed that LWD was not homogenous throughout the canopy and varied significantly according to sensor position. Significant differences in LWD during a 12-h period were detected for height (top, middle, and bottom), horizontal position (west, west-central, east-central, and east) and "season-rain" fixed effects (Table 1). The interaction between the "season-rain" class with height and horizontal positions was not significant (Table 1), which indicates that during the summer and winter seasons, trees have similar patterns of variation in LWD at each height and horizontal position.

The statistical analysis by "season-rain" revealed that LWD heterogeneity was significant even during rainy days when evaluated as a group (Table 2). During rainy days, the wetness was due to both rainfall and dew events, so this result is based on a combined effect of dew and rainfall during the day. Dew events were reported during late night and early morning, while rainfall periods occurred randomly at daytime and nighttime. Significant interactions of height and horizontal positions were observed for winter but not for summer.

No significant differences in LWD were detected among heights and horizontal positions for the daytime rain events (Table 3), suggesting that the variability of LWD tended to be minimized with rainfall. However, the LWD influence of dew contributed to make LWD heterogeneity significant among heights even for rainy days when analyzed as a group. During daytime rain events the entire canopy was wetted at the beginning of the rainfall. Even though there was no statistical difference among heights, the mean LWD of the rain events during daytime (Table 4) indicated an average dry-off in the top canopy about 32 min before the middle canopy and 16 min before the bottom canopy.

Table 1. Generalized Linear Mixed Model (GLMM) type III test for fixed effects of LWD in a 12-h period.

Fixed effects	DF[z]	*P* value
Height	2	<0.0001
Horizontal	3	0.0003
Height × Horizontal	6	0.0429
Season-rain	2	<0.0001
Season-rain × Horizontal	4	0.3573
Season-rain × Height	6	0.7041

[z]DF, degrees of freedom.

Table 2. Generalized Linear Mixed Model (GLMM) type III test for fixed effects by season of leaf wetness duration (LWD) in a 12-h period.

		P value		
		Summer		Winter
Fixed effects	DF[z]	No-rain days	Rain days	No-rain days
Height	2	<0.0001	0.001	<0.0001
Horizontal	3	0.0033	0.0404	0.0016
Height × Horizontal	6	0.101	0.7363	0.0036

[z]DF, degrees of freedom.

Table 3. Generalized Linear Mixed Model (GLMM) type III test for fixed effects of leaf wetness duration (LWD) during seven daytime rain events, which occurred after 3 PM and therefore eliminated influence of dew.

Fixed effects	DF[z]	*P* value
Height	2	0.5388
Horizontal	3	0.5869
Height × Horizontal	6	0.9306

[z]DF, degrees of freedom.

Table 4. Mean leaf wetness duration (LWD) of seven rain events during daytime which occurred after 3 PM and therefore eliminated influence of dew.

Height	LWD (h)
Top	4.10
Middle	4.64
Bottom	4.36

The mean daily duration of rainfall for the daytime rain events was 0.9 h, whereas the average LWD (excluding dew) was 4.4 h, implying that it took on average 3.5 h to dry the canopy during daytime after rain.

The LSM multiple comparisons for height showed that the top canopy positions have significantly longer LWD compared to the middle and bottom canopy positions (Table 5 and Figure 2). Mean daily LWD at the middle and bottom canopy positions were not significantly different. This pattern was consistent both during the summer and winter seasons. The differences in mean daily LWD between top and bottom for non-rainy days (dew only) were 2.9 h and 2.6 h during the summer and winter, respectively. The difference between top and bottom LWD during rainy days in the summer was approximately 2.5 h. The east-central and west-central horizontal positions had the longest LWD (Table 5) but the differences among horizontal positions were not as pronounced as the differences among heights.

Rain days during the summer season show longer mean LWD compared to non-rainy days (Table 6). During non-rainy days, dew is the main source of wetness. Mean daily LWD is expected to be greater during the summer than during the winter since the relative humidity and dew point temperature of the air in the summer (warm air mass) are higher than during the winter. Lower wind speed and higher relative humidity observed at the nearby FAWN station (Table 7) during summer rain-free days explains longer mean LWD compared to winter.

Estimation of within-canopy LWD from sensors over turfgrass. The estimation of daily LWD within citrus canopies based on measurements made by the sensors installed in the nearby FAWN station at 0.30 m and 2 m (0.98 ft and 6.56 ft) above turf grass showed that measurements from the sensor at 0.30 m (0.98 ft) (Fig. 3A) closely matched and better represented the LWD measured at the top – east central position of the canopy than measurements from the sensor at 2 m (6.56 ft) (Fig. 3B). It should be noted that the top-east central position within the canopy had the longest LWD and is representative of the most favorable conditions for disease development. The slope of the linear regression equation of the top-east central position is approximately 1.05 and the intercept 10.92, representing a constant bias toward underestimation of 10.92 min and an average underestimation of 5% by the sensor at the station at 0.30 m (0.98 ft) over turf grass (Fig. 3A). The mean difference (21 min) and the mean absolute error (41 min) are small enough to allow use of LWD at the nearby weather station sensor at 0.30 m (0.98 ft) over turf grass as a surrogate of LWD at the top of the canopy in many operational plant disease management schemes. The sensors over turf grass gave weak estimates of LWD in the middle (Fig. 3C) and bottom (Fig. 3D) canopy positions with a tendency to overestimate LWD.

The observed LWD spatial heterogeneity was significantly different during rainy days and rain-free days. LWD was significantly longer at the top canopy compared to the middle and bottom both during the summer and winter seasons. During rainy days the wetness was the result of a combined effect of dew and rainfall. The variability of LWD tended to be minimized with rainfall; therefore, the longer LWD at the canopy top during rainy days was result of an early dew formation at the top canopy and not by an uneven dry-out process after rain events.

Table 5. Mean daily leaf wetness duration (LWD) in hours (LSM multiple comparison for height and horizontal position effects).

	Summer		Winter
Factors	No-rain days	Rain days	No-rain days
Height			
Top	5.4 a[z]	12.2 a	3.2 a
Middle	2.8 b	9.8 b	0.9 b
Bottom	2.5 b	9.7 b	0.6 b
Horizontal			
East-central	4.5 a	11.6 a	2.2 a
West-central	3.8 a	11.1 a	1.7 ab
East	3.5 ab	9.8 b	1.2 b
West	2.5 b	9.7 b	1.2 b

[z]Numbers in the same column followed by the same letter are not significantly different at the 5% probability level.

During no-rain days, when the main source of wetness is dew, longer LWD at the top canopy can be explained as the result of radiational cooling at the canopy top which is directly exposed to the sky, promoting dew formation. The leaves at the top delay the heat loss of the leaves at the middle and bottom canopy therefore delaying the formation of dew at those height levels (Batzer et al., 2008; Sentelhas et al., 2005). Dew accumulation varies significantly depending on the location within the crop canopy because its formation is affected by vertical profiles of air temperature, vapor pressure, incoming and outgoing radiation and wind (Beysens, 1994; Huber and Gillespie, 1992).

Longest LWD due to dew at the top canopy should be expected for citrus in humid climates because the dewfall (dew originated from air) process dominates, whereas for irrigated land in semiarid climates the opposite or different response could be expected. The dew-rise (dew originating from soil) process is the primary source of dew for irrigated land in semiarid climates because atmospheric humidity is relatively low (Jacobs et al., 1990). In a semiarid region of New South Wales, Australia, Penrose and Nicol (1996) found that the center of the apple tree canopy was wet on significantly more occasions than other locations within the tree. These remarks show that the LWD spatial variability patterns due to dew could vary according to the regional climatic conditions, which affect the dewfall and dew-rise processes. Longest LWD at the east-central horizontal positions could be related to the prevalent westerly winds in Aug. 2008 and to the fact that central positions are more exposed to the inter row space.

The spatial variability of LWD within the citrus canopies showed that this variable is affected not only by weather conditions but also by plant structure and height, which affect the crop microclimate. The variability of LWD within crop canopies has been investigated by Batzer et al. (2008), Sentelhas et al. (2005), and Santos et al. (2008), and all agreed that the LWD showed significantly different patterns of variation within the crop canopies. Our results indicate that the same is true for citrus canopies. The spatial pattern in height coincides with the results obtained by Batzer et al. (2008) for apple trees in Iowa, which also has a humid summer environment. They demonstrated that LWD at

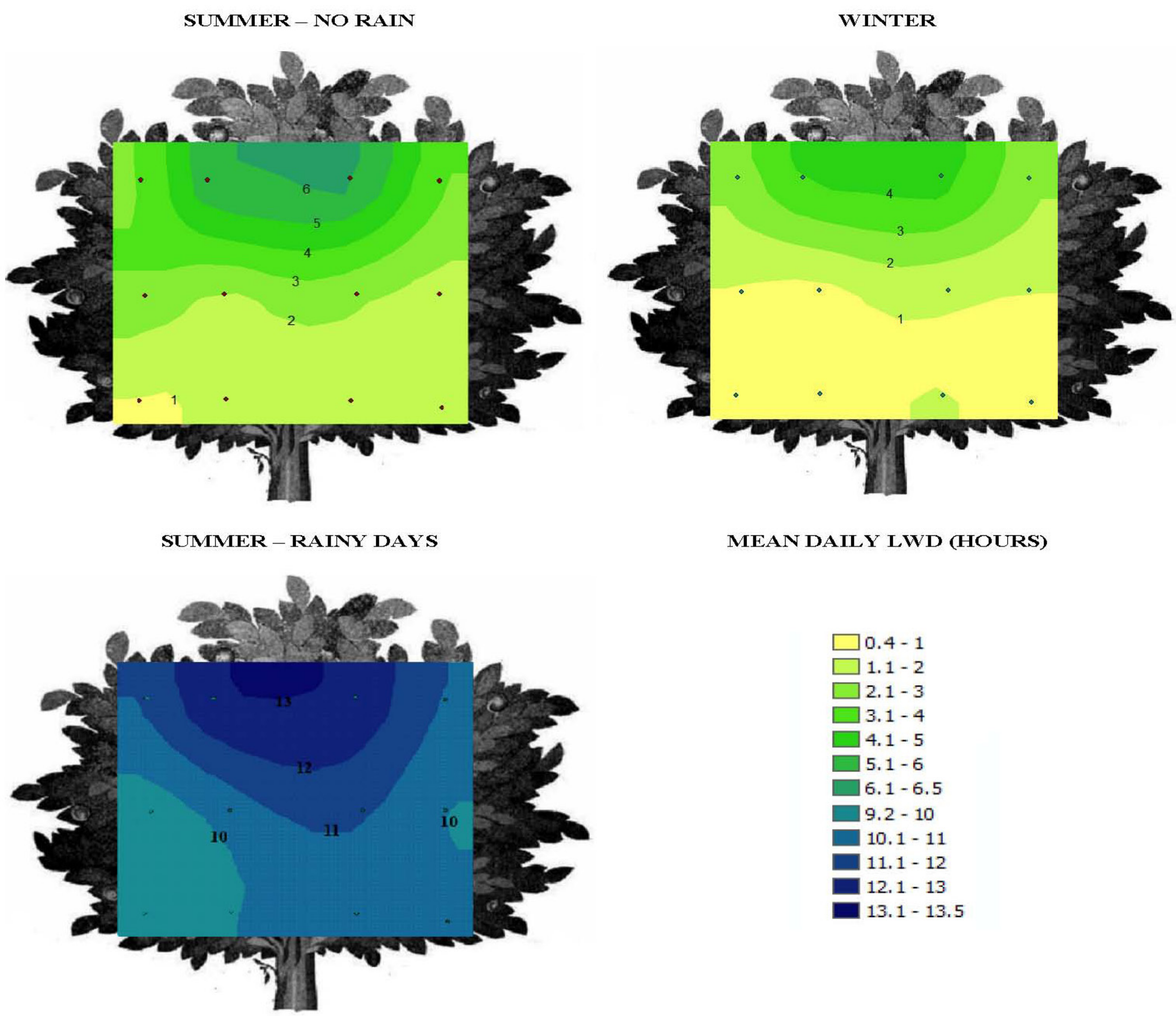

Fig 2. Mean daily leaf wetness duration (LWD) in hours. Daily data sets were partitioned into rainy (measured rainfall ≥ 0.25 mm) and no-rain days.

Table 6. Mean daily leaf wetness duration (LWD) in hours, by season and rainfall.

Season	Rain	Mean daily LWD (h)
Summer	Yes	10.5 a[z]
Summer	No	3.6 b
Winter	No	1.6 c

[z]LSM multiple comparison. Numbers in the same column followed by the same letter are not significantly different at the 5% probability level.

the top of an apple tree canopy averaged about 3 h more per day than the lower western portion of the canopy.

The LWD at the top of a citrus canopy can be reasonably estimated from measurements of LWD at the FAWN station sensor at 0.30 m (0.98 ft) over turf grass. This finding agrees with the results obtained by Sentelhas et al. (2005) for five different crops (apple, coffee, grape, maize, and muskmelon), where the comparison by geometric mean regression analysis showed that a LWD sensor

Table 7. Mean hourly weather parameters values per evaluation period: 11 d for summer-no rain, 20 d for summer-rain days and 30 d for winter.

	Summer		Winter
	No-rain	Rain	No-rain
T min (°F)[z]	73.8	73.9	47.2
T max (°F)	91.8	88.0	71.5
T avg (°F)	81.9	79.1	58.9
T_d (°F)	72.5	73.9	45.5
VPD (kPa)	1.00	0.57	0.69
RH (%)	75.4	85.4	65.8
SR ($W \cdot m^{-2}$)	221.1	138.3	190.7
Wind speed (mph)	3.1	4.6	4.7

[z]T, temperature; T_d, dew point temperature; VPD, vapor pressure deficit; RH, relative humidity; SR, solar radiation.

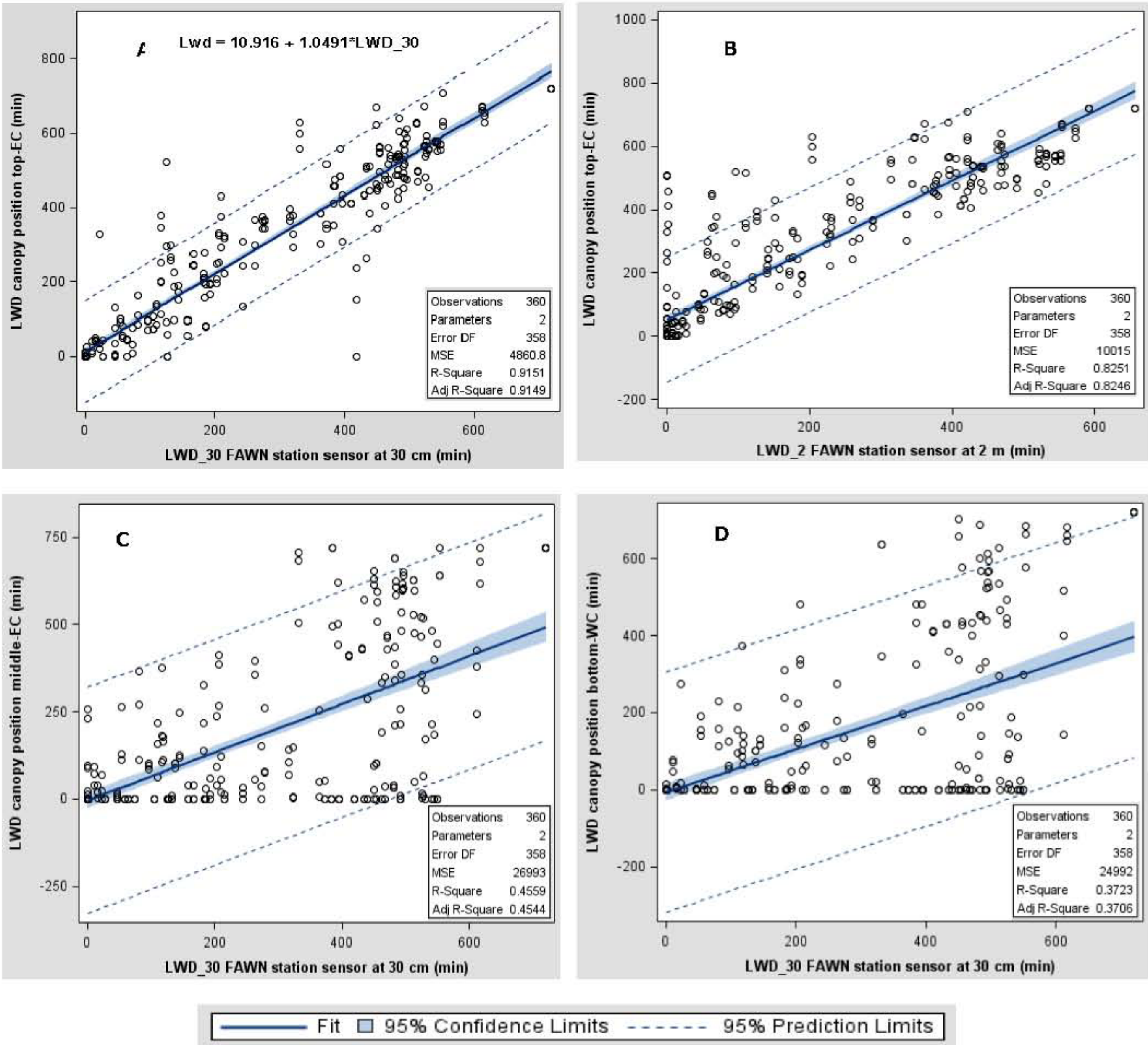

Fig. 3. Linear regression between leaf wetness duration (LWD) measured at the canopy top-EC position and LWD measured at FAWN station sensor at (**A**) 0.30 m (0.98 ft) over turfgrass and (**B**) 2.0 m (6.56 ft) over turfgrass. Linear regression between LWD measured at the FAWN station sensor at 0.30 m over turf grass and LWD measured at the canopy (**C**) middle-EC position and (**D**) bottom-WC position.

at 0.30 m over turf grass provided accurate estimates of LWD at the top canopy but poorer estimates for wetness within the crop canopy. Moreover, Zhang and Gillespie (1990) showed that measurements made at a nearby weather station could be adjusted to in-canopy LWD with acceptable accuracy. They demonstrated that differences between modeled LWD using only standard weather station data and measured wetness duration on shaded maize leaves at 0.80 m (2.62 ft) were within 14% (25 min) of the actual wetness duration. These findings imply that data measured at nearby weather stations can be used as substitutes for canopy LWD measurements in disease warning systems, eliminating some mechanical risks and practical considerations related to having sensors within the crop canopy to estimate leaf wetness.

Conclusions

The spatial variability of LWD within citrus canopies in central Florida (humid climate) showed a constant pattern of longest LWD at the top canopy during rainy and rain-free days. The variability of LWD tended to be minimized with rainfall; therefore, the longest LWD at the canopy top during rainy days was the result of an early dew formation at the top canopy. The top of the canopy is directly exposed to the sky and is generally the first part of the canopy to exhibit wetness, both during dew and rain events. However, during daytime rain events, the top of the canopy is expected to receive more solar radiation and stronger wind than the other positions, resulting in a faster dry-off and hence reducing the difference in LWD between the top and lower parts of the canopy. These results demonstrate that the crop-canopy microclimate, which is influenced by weather factors and the crop structure and height, controls the wetness duration. Longest mean daily LWD due to dew was reported during summer conditions. The understanding of the spatial heterogeneity of LWD within citrus canopies may allow us to improve the performance of disease warning systems that rely on LWD as input.

The nearby weather station sensor at 0.30 m (0.98 ft) over turfgrass provided accurate estimates of LWD at the top of the canopy where the maximum LWD was observed. These measurements represent a good alternative for an accurate LWD estimation at the citrus canopies, which could be used in many operational plant disease management schemes.

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