SPATIAL VARIABILITY OF LEAF WETNESS DURATION IN CITRUS CANOPIES

By

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To Maritza, Pedro, Mileny and Jose, who offered me unconditional love and support

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Leaf wetness duration (LWD) is a key parameter to disease warning systems as input to biological modeling of infection of many plant diseases in crops. However, within-canopy LWD heterogeneity can impact performance of disease-warning systems. The 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 three citrus trees in central Florida at twelve canopy positions. Dielectric leaf wetness sensors were used to estimate leaf surface wetness and were placed at three height positions above the ground in a northward leaning position at an inclination of 45 degrees to horizontal. At each height, sensors were placed at four horizontal positions approximately 0.6 m apart along an east-west transect. Three CR10X data loggers were used to record measurements every 15 minutes during August 2008 and February 2009. The analysis of LWD measurements revealed statistical heterogeneity among sensor heights and horizontal positions. LWD was significantly longer ($P<0.0001$) at the top canopy compared to the middle and bottom positions during rainy days and no-rain days. During no-rain days, the main source of wetness was dew, while during the rainy days; the LWD was the result of rainfall and dew events combined in a day. Rain wets the entire canopy and minimizes the LWD differences among heights; therefore, the longer LWD at the canopy top

during rain days was result of dew events during the nighttime and early morning. The differences in daily mean LWD between top and bottom canopy during a 31-day period of time in the summer were 2.9 h and 2.5 h during no-rain and rain days, respectively. The difference in mean daily LWD during a 30–day 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 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 in canopy measurements of LWD are used as inputs to disease-warning systems.

CHAPTER 1
INTRODUCTION

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 is dependent on the properties of surfaces as well as the atmospheric conditions and its occurrence is linked to with 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 the two 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 to 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 the most spatially heterogeneous weather input to 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 (Sentelhas et al., 2004a; Gleason et al., 2008). Batzer et al. (2008) investigated the influence of the spatial variability of LWD within the apple trees canopies on the performance of a warning system for Sooty Blotch and Flyspeck (SBF). They found 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 days 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 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 (PFD), and huanglongbing also commonly called citrus greening (Spann et al., 2008).

Prediction models for Alternaria brown spot and postbloom fruit drop had been developed as disease control tools. The Alter-Rater model was developed for control of Alternaria brown spot, caused by *Alternaria alternata*, which result serious yield losses 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 resulted in fewer sprays compared to a calendar spray schedule and its use results in better disease control.

In addition, a model for postbloom fruit drop, caused by *Colletotrichum acutatum*, has been developed to assist growers in determining the need and timing for 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, the total rainfall, and the LWD for the last 5 days (Peres et al., 2009). 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.

These disease warning systems designed to ensure acceptable disease control with the reduction of input costs by minimizing the number of pesticide applications rely on LWD data as input. Thus, a profound understanding of the spatial heterogeneity of LWD within the canopy is essential to improve the performance of disease warning systems. Citrus plants are large shrubs or small trees where a wide range of leaf wetness variability may be expected throughout the canopy.

Objectives

The main goal of this thesis is to evaluate if LWD patterns vary among different positions within the citrus canopies cultivated in central Florida. The specific objectives are to:

1. Determinate and understand the spatial heterogeneity of LWD within canopy of citrus.
2. Compare the spatial variability of LWD during summer and winter conditions.
3. Compare the LWD patterns within citrus canopies with measurements observed in a nearby Florida Automated Weather Network (FAWN) station.

CHAPTER 2
LITERATURE REVIEW

Leaf Wetness Duration (LWD)

Leaf wetness duration is the period of time during which free water is present on the outer surfaces of crop plants (Klemm et al., 2002). It is a property of surfaces as well as the atmosphere, and caused by dew, rainfall, fog, and irrigation. Leaf wetness is not usually considered as a micrometeorological factor by atmospheric physicists and is not a well-defined variable (Huber and Gillespie, 1992). Depending on the tissue hygroscopicity and physical characteristics of the leaves, it may consist of individual drops or of water films of thickness between a few nm or µm (Klemm et al., 2002).

LWD is a non-standard meteorological parameter and there is no widely accepted standard for measuring or estimating it (Gleason et al., 2008). The lack of a suitable standard for measuring or estimating it has many consequences such as: it is impractical to estimate LWD climatic databases for large regions; LWD interpretation must to be made according to the protocol under which it was collected and will vary for different crops (Magarey, 1999).

Importance of LWD

Leaf wetness is a key parameter for agriculture since it plays an important role with plant diseases, insect activity, deposition of pollutants on crops (Huber and Gillespie, 1992), the effectiveness of applied pesticides, the curing and harvesting of many crops (Davis and Hughes, 1970), and in the moisture balance of arid and semiarid regions of the world (Getz, 1992). Furthermore, the frequency and duration of water on leaf surfaces have important consequences for plant growth and photosynthetic gas exchange (Brewer and Smith, 1997).

Leaf wetness and plant pathogen development. The influence of the weather conditions on plant disease development has been known by growers and well-documented by scientist for a very long time. The key weather variables that trigger many plant disease outbreaks are temperature and LWD (Gillespie and Sentelhas, 2008; Campbell and Madden, 1990). The incidence and severity of numerous plant diseases depend on the interaction of temperature and free moisture. LWD influences epidemiological episodes affecting infection and sporulation processes on several foliar plant pathogenic fungi and favors any plant pathogen whose spores or cells require a water film to germinate or divide (Huber and Gillespie, 1992). Some fungal pathogens require continuous wetness episodes lasting several days to sporulate, although sporulation can occur during a succession of short wet periods interrupted by dry intervals. Bacteria require a water film to increase on the foliage portions of their host plants (Wallin, 1967). The number of plant pathogens influenced by leaf wetness are too numerous and will not be discussed in this document.

Agro-meteorological Applications of LWD

Every facet of agriculture depends on the weather; therefore the application of meteorology in agriculture plays an important role. Agricultural decision makers derive benefit from agro-meteorological applications, such as farmers ensuring acceptable disease control by the reduction of the input costs by minimizing the number of pesticide applications based on disease-warning systems (Stefanski et al., 2007).

The disease-warning systems, also known as disease forecasts, are decision-support tools that model the disease progress using information about the weather, the crop and the pathogen. Warning systems advise growers when they need to take an action, usually application of pesticides, to prevent disease outbreaks and avoid economic losses (Gleason et al, 2008). Gillespie and Sentelhas (2008) assured that the measurements or estimations of LWD provided by agro-meteorologists have allowed plant pathologists to devise weather-timed spray schemes which often reduce the number of sprays required to control plant diseases, thus lowering costs and benefitting the environment.

Many U.S. companies provide site-specific estimates for air temperature, wind speed, relative humidity, and LWD, not only in hind cast mode but also as forecasts up to 72 h into the future. A reliable forecast of the weather parameter could offer growers two important benefits: opportune access to weather data and the ability to anticipate disease outbreaks (Kim et al., 2006).

The application of meteorology to overcome a disease outbreak involves a thorough understanding of the disease triangle which includes the complex life cycle of the pathogen and its host, as well as the environmental conditions that influence growth and development (Stefanski et al., 2007). The most important weather variables that prompt many plant disease outbreaks are temperature and moisture; where the moisture variables involved are relative humidity and LWD (Gillespie and Sentelhas, 2008).

Relative humidity can be physically well-defined, whereas leaf wetness duration (LWD) is a parameter difficult to measure or estimate because different various portions of leaves and canopies wet and dry at different times (Huber and Gillespie, 1992). In contrast to air temperature, LWD is a difficult variable to measure or to estimate because it is driven by both atmospheric conditions and their interactions with the structure and composition of the vegetative community (Sentelhas et al., 2004a).

Because of its influence and importance in disease development, LWD is a key parameter to decision support systems as input to biological modeling of infection of fungal diseases in crops. The risk of outbreaks of many plant diseases is directly proportional to this environmental variable (Sentelhas et al., 2006). LWD is the most spatially heterogeneous weather input to warning systems. It varies not only with weather conditions but also with the type of crop, its developmental stage, the position, angle, and geometry of individual leaves (Gleason et al., 2008). During dew periods, different micro-sites on a single leaf can vary in LWD by several hours per day (Sentelhas et al., 2005). Within-canopy LWD heterogeneity can impact performance of disease-warning systems (Batzer et al., 2008).

Disease warning systems for citrus. Citrus 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 directly influenced by weather variables currently present in Florida include greasy spot, Alternaria brown spot, melanose, canker, postbloom fruit drop (PFD) and scab (Chung and Brlansky, 2006; Spann et al., 2008).

Prediction models for Alternaria brown spot and postbloom fruit drop had been developed as disease control tools. The Alter-Rater model was developed for controlling Alternaria brown spot, caused by *Alternaria alternata*, which results in serious yield losses 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-Model resulted in fewer sprays compared to a calendar spray schedule and its use results in better disease control.

In addition, a model for postbloom fruit drop, caused by *Colletotrichum acutatum*, has been developed to assist growers in determining the need and timing 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, the total rainfall and LWD for the last 5 days (Peres et al., 2009). 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. These two disease warning systems for citrus rely on LWD as input. A good understanding of the spatial variability of LWD within citrus canopies could result in improved the performance of these models.

History

The leaf wetness produced by dew has been a subject of study throughout the history. Aristotle made the observation that dew appears on calm and serene nights. Then, many ancient scientists carried out dew experiments, but they did not understand why dew collects on some surfaces far more than on others (Möller, 2008). The first attempt to understand the physics of this phenomenon was the demonstration of dew formation in 1814 by William Charles Wells. Wells (1814) showed that dew resulted from the effects of heat radiation from the earth's surface during the absence of the sun, where bodies become colder than the neighboring air before dew is formed.

Most of the important developments in leaf wetness research have occurred since the 1940s when Howard Penman developed a theory model for the estimation of evaporation based on the energy balance and mass transfer (Howell and Evett, 2004). The Penman model has been the basis for the estimation models of leaf wetness used at the present time. In 1954, Hirst developed a first mechanical method for recording surface wetness duration on plant surfaces and by the mid-1980s, the mechanical LWD sensors were giving away to electronic sensors and automated dataloggers (Gleason et al., 2008). Since then, empirical and physical models had also been developed to estimate this parameter using data originating from improved electronic surface wetness recorders and weather data collected at nearby stations. Unfortunately, despite a large volume of research on LWD and its widespread use in agriculture, LWD is a non-standard meteorological parameter and there is no widely accepted standard for measure or estimate it (Magarey, 1999).

Causes of LWD

The occurrence of leaf wetness has links to the occurrence of precipitation, fog, irrigation, dew and to a lesser extent to guttation (Davis and Hughes, 1970). Leaf wetness is formed either through deposition of hydrometeors such as rain and fog droplets from the atmosphere or through condensation of water vapor (dew) on the leaf surface. Hydrophilic aerosol particles on the leaf surfaces may support or enable the formation of leaf wetness at high relative air humidity (Klemm et al., 2002). During rainfall events or overhead irrigation periods, water falls on the canopy with varying intensity (Huber and Gillespie, 1992).

Dew formation. For dew to form on a leaf, the leaf surface temperature must decrease below the dew point temperature of the ambient air (Beysens, 1994). Actually, dew forms on a leaf as the result of radiative cooling of the vegetative surfaces and not because of a drop in air temperature (Klemm, 2002). The dew formation is affected by vertical profiles of air temperature, vapor pressure, incoming and outgoing radiation and wind. Thus, dew accumulation varies significantly depending on the location within the crop canopy (Huber and Gillespie, 1992).

Dew on leaves and other exposed surfaces can originate from two separate sources; when it is originated from the air is called dewfall and dewrise when originating from the soil (Jacobs and Nieveen, 1995). Dew deposition moderates and sometimes stops nightly cooling, thus protecting the plants against morning frost (Wallin, 1967). The surface properties modify the conditions of formation of the liquid phase because they alter the thermodynamic conditions for condensation (Beysens, 1995).

Leaf Wetness Variability

The leaf area, plant structure, planting system, arrangement of the plants in the field, and crop height are factors that influence the crop-canopy microclimate. These factors influence radiation interception and balance and determine temperature, humidity and wind regimes within the crop canopy allowing various portions of the leaves and canopies to become wet and dry at different times (Huber and Gillespie, 1992).

Brewer and Smith (1997) found in the central Rocky Mountains that a survey of 50 subalpine/montane species showed that structural characteristics associated with the occurrence and duration of leaf surface wetness differed among species and habitats. The leaf surface of open-meadow species were less wettable, and had lower droplet retention and more stomata than adjacent understory species. In addition, leaf trichomes reduced the area of leaf surface covered by moisture. The chemistry of the cuticle and the surface roughness of leaves influence the extent to which surface moisture adheres to leaves. Their study denotes the influences of structural characteristics of leafs and habitats on the LWD occurrence.

The variability of LWD within crop canopies has been investigated by Batzer et al., 2008, Sentelhas et al., 2005 and Santos et al., 2008, all agreed that the LWD showed significantly different patterns of variation within the crop canopies. 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 for the cotton crop, no difference was observed between the top and lower third of the canopy. Moreover, Sentelhas et al. (2005) found that the LWD was longer at the top in apple and maize, whereas for grapes, cultivated in a hedgerow system and coffee plants, average LWD did not differ between the top and inside canopy.

In addition, Batzer et al. (2008) found in apples trees that the upper eastern portion of the canopy had the longest mean daily LWD and was the first site to form dew and last to dry. When LWD measurements from several canopy positions were put into the warning system for sooty blotch and flyspeck in apples, the timing of occurrence of a fungicide-spray threshold varied by as much as 30 days among canopy positions. This finding revealed the influence of the spatial heterogeneity of LWD measurements within the canopy in the performance of the warning system for sooty blotch and flyspeck in apples.

Jacobs et al. (2005a) developed a relatively simple physical model to simulate the wetting and drying processes in different layers within a lily canopy in Lisse, Netherlands; and a field experiment was carried out to verify this model. The model results suggest that the leaf wetness period and the early morning drying process in the canopy starts at the top canopy and from there penetrates into the canopy; but the longest leaf wetness duration occurs at the bottom of the canopy.

Gleason et al. (2008) stated that the LWD differences found within canopy were more accentuated when dew was the main source of wetness, whereas differences were much less pronounced during rainfall-associated wet periods, because rainfall tends to minimize these differences. Usually, the greatest dew duration is associated with humid climates (Jacobs et al., 1990). Continental climates are more likely to have more pronounced LWD canopy heterogeneity because LWD is predominately caused by dew rather than rain (Gleason et al., 2008). Moreover, LWD differences within the canopy will be more marked during winter than summer because dew is the main source of wetness throughout winter.

All these studies show that the heterogeneity of LWD within canopy can vary with the type of crop canopy and with climate. This immense heterogeneity poses a formidable challenge for measuring or estimating LWD.

Measurements of LWD with Electronic Sensors

One of the most common methods to measure LWD is with an electronic grid. Getz (1992), in the report on the measurement of leaf wetness for the World Meteorological Organization, recommend that the electronic artificial leaf wetting sensor when integrated into a data logging system is the most powerful resource for measurement of LWD.

Currently, the two kinds of sensors most used by researchers operate on the principle of electrical resistance and capacitance (Gleason et al., 2008). These sensors provide an indirect measurement of LWD (Magarey et al., 1999). The electronic sensors based on resistance sensed the presence of wetness as a drop in electrical resistance across two adjacent circuits etched onto a printed-circuit grid (Davis and Hughes, 1970). Later studies found that coating the resistance sensor with latex paint improved not only the precision of the sensors but also their sensitivity to detect wetness promoted by small water droplets (Sentelhas et al., 2004b; Lau et al., 2000).

The dielectric leaf wetness sensors, which were used in this study, are a most recent innovation in flat plate sensor design and are based in the capacitance principle. They were developed to estimate by inference the wetness of nearby leaves by measuring the dielectric constant of the sensor's upper surface. The LWS-L (Decagon Devices, Inc., Pullman, WA) is designed to approximate the thermodynamic properties and closely matches the radiative properties of most leaves; therefore, it is able to mimic the wetness state of the real leaves. Spectroradiometer measurements indicate that the overall radiation balance of the sensor closely matches that of a healthy leaf (Decagon Devices, Inc., Pullman, WA).

An important consideration is that the size and shape of the LWD sensor should be similar to the leaf or plant structure to be measure surface wetness (Suttton et al., 1984; Magarey, 1999). Researchers have also attempted to mimic fruit shape in sensor construction (Sutton et al., 1984), and a cylindrical shaped sensor has been found to be useful to mimic LWD in onions leaves (Gillespie and Duan, 1987).

Practical Use of Sensors: Sensor Placement, Calibration and Accuracy

LWD is a difficult variable to measure since there is no observation standard for the sensor and the exposure conditions (Magarey, 1999). The performance of the sensors to monitor accurately vegetative wetting depends on the correct exposure of the sensor in the field (Davis and Hughes, 1970). Lau et al. (2000) found that the deployment angle and painting of the sensor surface can significantly affect accuracy and precision of dew-duration measurements, while the compass direction of orientation had no significant effect on response to dew onset and dry-off. Magarey (1999) recommended for the northern hemisphere that the sensor should be oriented north to minimize the interception of solar radiation; because this orientation favors the longest wetness duration.

Sentelhas et al. (2004a) demonstrated that sensors deployed 30 cm above turfgrass and between 15° and 45° to horizontal showed the smallest errors in relation to visual observations of turfgrass wetness. A flat plate LWD sensor deployed horizontally stayed wet an average of 38 and 56 min longer than plates tipped down 30-45° from horizontal in Elora, Canada and Piracicaba, Brazil, respectively; and plates tipped at 30-45 degrees usually do a better job of matching the wetness on nearby crops (Sentelhas et al., 2004b). For the angle of deployment of the sensors installed at 30cm over turfgrass, there was no significant difference especially among the sensors at 15°, 30° and 45°. Also, they identified significant differences among senso r heights, showing that the height of the sensor had a stronger effect on LWD measurements than the angle of deployment.

Since there is no standard on how or where to place the LWD sensors, users position them in a variety of ways, even within the same crop canopy (Gleason et al., 2008). Locating LWD sensors within the crop canopy bring some mechanical risks, such as damage from mowers, sprayers, and cultivators (Gleason et al., 2008), and practical considerations such as regular maintenance.

Sentelhas et al. (2005) found that LWD measurements made at 30 cm over turfgrass were quite accurate estimates of LWD at the top of the apple, coffee, grape, maize and muskmelon crops. Moreover, Zhang and Gillespie (1990) found that LWD modeled with data from nearby weather station data can estimate in-canopy LWD measurements on corn leaves with acceptable accuracy. These findings suggest that data measured at nearby weather stations can be used as surrogates for canopy LWD measurements (Gleason et al., 2008), which eliminates the mechanical risks and practical considerations mentioned above. The lack of standards for sensor placement has encouraged researchers to explore alternative approaches such as LWD model simulation.

Leaf Wetness Simulation Models

Many predictive models, both physical and empirical, have been developed to estimate LWD as an alternative to sensor estimation. Physical models are based on the energy balance and mass transfer approach. This approach can be highly accurate (Pedro and Gillespie, 1982), but model complexity is a disadvantage for operational use (Sentelhas et al., 2008). The Penman-Monteith approach to modeling LWD is based on the physical principles of dew deposition and dew or rain evaporation and incorporates empirical wetness coefficient to convert reference LWD (sensor located at a weather station) into crop LWD (Sentelhas et al., 2006). The main advantage of the Penman-Monteith approach in relation to the models based on energy balance (Pedro and Gillespie, 1982) is the elimination of the requirement for an air temperature measurement at crop level. Sentelhas et al. (2006) found that the Penman-Monteith model may be a useful reference index to estimate crop LWD for use in plant disease schemes. Even though these physical simulation models have shown accurate results for LWD estimation, the main disadvantage lies in the numerous micrometeorological measurements that the models require as input, which are not generally available (Getz, 1992).

On the other hand, empirical models use statistical best-fit algorithms to help choose parameters and functions that yield the most accurate estimates of LWD (Gleason et al., 2008). These models are accurate for regions where they were developed, but not outside of those locations (Gleason et al., 2008). Sentelhas et al. (2008) found that LWD can be estimated with acceptable accuracy using a simplest empirical method based only on relative humidity above a specific threshold if it is calibrated locally. In general, the RH > 90% is a good estimator of LWD, but the use of specific thresholds for each location improves accuracy of the RH model substantially. It suggests that under the Florida weather conditions long periods of leaf wetness duration could be expected.

Moreover, Kim et al. (2005) evaluated two empirical LWD models developed in the mid-western U.S., the CART/SLD/Wind model and the Fuzzy model, to assess their accuracy and adaptability to the tropical climate of northwestern Costa Rica. They found that the accuracy of the Fuzzy model was substantially improved when a correction factor was utilized, indicating that this model could be adjusted to estimate LWD in tropical regions with acceptable accuracy. These findings suggest that these models could be used to estimate LWD in different regions where they were developed with local calibration; but local calibration signifies a disadvantage because it represents an additional step to the model adaptation.

Calibration and validation of any LWD model remains a critical issue (Magarey, 1999). Some of the inputs needed in the models are not commonly measured by agricultural weather stations, such as net radiation, while others must be derived from standard weather stations. Even when measurements are available, spatial variability of wetness duration may make it difficult to use the measurement at sites >30 km distant from a weather station (Rao et al. 1998).

The basic problem with most of these approaches is that there is no recognized standard method of making actual leaf wetness measurements. The World Meteorological Organization and the European and North American Plant Protection Organizations have recommended the development of a standard for leaf wetness measurement (Anonymous, 1990). Without a recognized standard, there cannot be any credible verification of a simulation model (Getz, 1992). The absence of a standard prevents the exchange or interpretation of data when different protocols or instruments are used for LWD estimation (Magarey et al., 1999).

Models to estimate LWD based on the physical principles, empirical procedures and hybrids of the two approaches (Gleason et al., 2008) have shown good portability and sufficiently accurate results for operational use. There appears to be no single “best method” to estimate LWD, but the need of electronic sensor side by side modeling is clear (Gleason et al., 2008). The standardization of the electronic sensors will allow credible verification of a simulation model. Moreover, LWD models are essential to forecast LWD values within canopy in order to use them in a disease warning system.

CHAPTER 3
MATERIALS AND METHODOLOGY

In this Chapter, the data collection design as well as the methodology and procedures used for data analysis will be presented.

Materials

Location

The experiment was located at the University of Florida, Citrus Research and Education Center (UF-CREC) in Lake Alfred, Florida (28° 06’ N, 81° 42’ W). Lake Alfred is officially the geographic center of Florida, and is located at 50 miles southwest of Orlando. Central Florida has a prevalent humid subtropical climate. Summers throughout the state are long, warm and fairly humid. Winters are mild with periodic invasions of cool to occasionally cold air. Florida’s proximity to the Atlantic Ocean and the Gulf of Mexico, and the state’s many lakes and ponds, together account for the high humidity and generally abundant rainfall, although precipitation can vary greatly from year to year and serious droughts have occurred.

The data were collected during 31 days in August 2008 and 30 days in February 2009 to represent the summer and winter seasons, respectively. The data were collected throughout summer and winter to compare the variability of LWD within canopy between these two seasons. We hypothesized that potential differences in LWD would be less significant during rainy days than during no-rain days. LWD canopy variability could be expected to be smaller in the summer than in the winter because summer generally has more rainy days than winter.

Sensor Placement

Twelve LWS-L sensors were installed in each tree of the three citrus species: grapefruit (*Citrus paradisi*) cv. Marsh Seedless, sweet orange (*Citrus ×sinensis*) cv. Hamlin, and a tangerine (*Citrus reticulata*) 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 about 1990 and are considered mature, bearing trees. The sensors recording LWD were placed at 0.6, 1.5 and 2.4 m 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 apart along an east-west transect (Figure 3-1). The sensors were placed in a northward leaning position at an inclination of 45 degrees to the horizontal (Figure 3-2B).

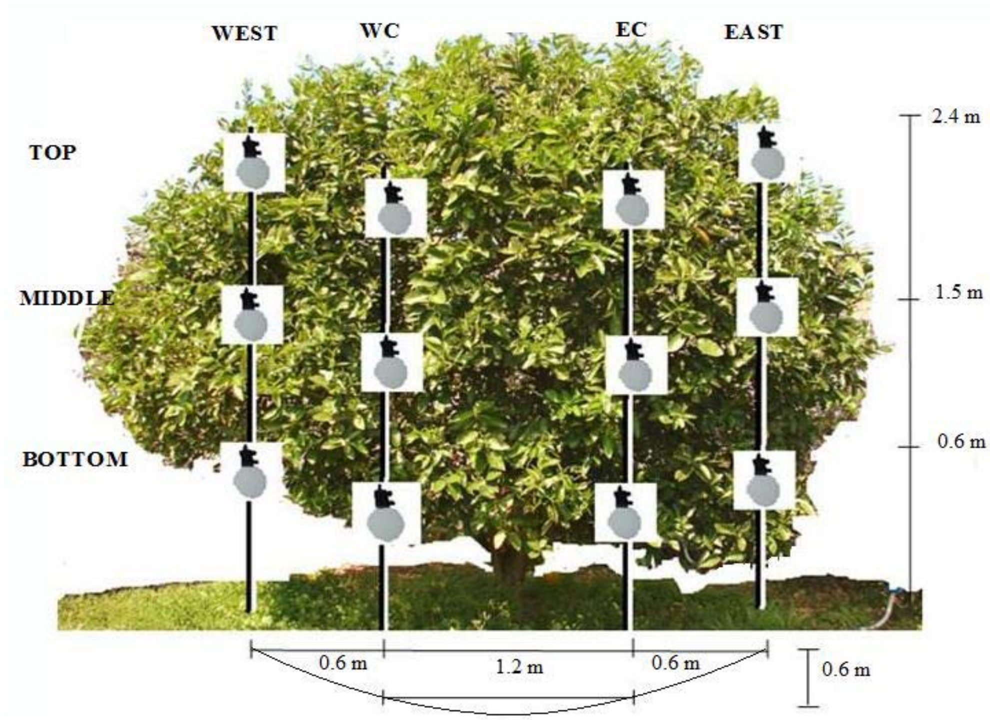

Figure 3-1. Location of leaf wetness sensors in citrus trees canopies. Sensors were located at 3 heights: top, middle and bottom and 4 horizontal positions: west, west-central (WC), east-central (EC), and east.

Sensors

The LWS-L dielectric leaf wetness sensors (Decagon Devices, Inc., Pullman, WA) were used to estimate by inference the wetness of nearby leaves by measuring the dielectric constant of the sensor's upper surface. The sensor (Figure 3-2A) consists of 0.65 mm thick fiberglass and it mimics the thermodynamic and radiative properties of real leaves. A typical leaf thickness is estimated at 0.4 mm and the heat capacity of the leaf is about 1425 J m^{-2} K^{-1}. This heat capacity is closely approximated by the sensor which has a heat capacity of 1480 J m^{-2} K^{-1}. Healthy leaves generally absorb solar radiation in much of the visible portion of the spectrum, but reflect much of the energy in the near-infrared. Spectroradiometer measurements indicate that the overall radiation balance of the sensor closely matches that of a healthy leaf. The leaves have a hydrophobic cuticle and the sensors have a hydrophobic surface coating (Decagon Devices, Inc., Pullman, WA).

The sensor is based on the capacitance principle and measures the dielectric constant of the entire upper sensor surface; moisture does not need to bridge electrical traces. Thus, the presence of water or ice anywhere on the sensor surface will be detected. It represents an advantage over the resistance-based sensors which require painting and user calibration (Decagon Devices Inc. 2007, Pullman, WA).In addition, the sensor has very high resolution, which gives it the ability to detect the presence of miniscule amounts of water or ice on the sensor surface. The sensor does not require painting and the individual sensor calibration is not normally necessary (Decagon Devices, Inc., Pullman, WA).

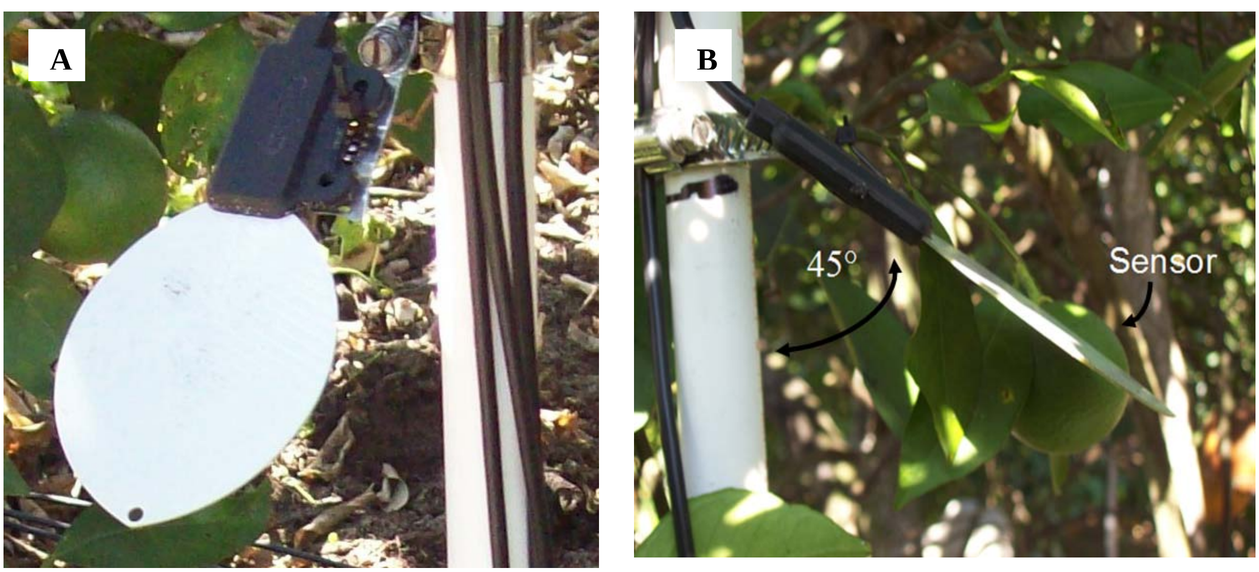

Figure 3-2. (A) LWS-L dielectric leaf wetness sensors; (B) Sensor's deployment angle

Operational principle of LWS-L dielectric leaf wetness sensor. The sensor output is an mV signal proportional to the dielectric constant of the measurement zone which is also proportional to the water amount on the sensor surface. Varying amounts of water on the surface of the sensor cause a sensor output (mV) proportional to the amount of water on the sensor's surface. The LWS-L measures the dielectric constant of a zone approximately 1 cm from the upper surface of the sensor. The dielectric constant is strongly dependent on the presence of moisture or frost on the surface. The dielectric constant of the water is much higher that of the air. (Decagon Devices, Inc., Pullman, WA).

The sensor requires an excitation voltage in the range of 2.5 to 5 volts. It produces an output voltage that depends on the dielectric constant of the medium surrounding the probe, and ranges between 10 to 50% of the excitation voltage. The Boolean threshold function was used to interpret the data. The threshold logger reading for the LWD sensor to be considered wet is > 274 mV which were obtained at 2.5 VDC excitation (Figure 3-3). The sensor output threshold corresponds to the minimum wet state identified. Most leaf wetness applications, such as disease warning systems or disease forecasting, just require knowledge of the presence of any water on the surface and information of the exact amount of water on the surface is not necessary.

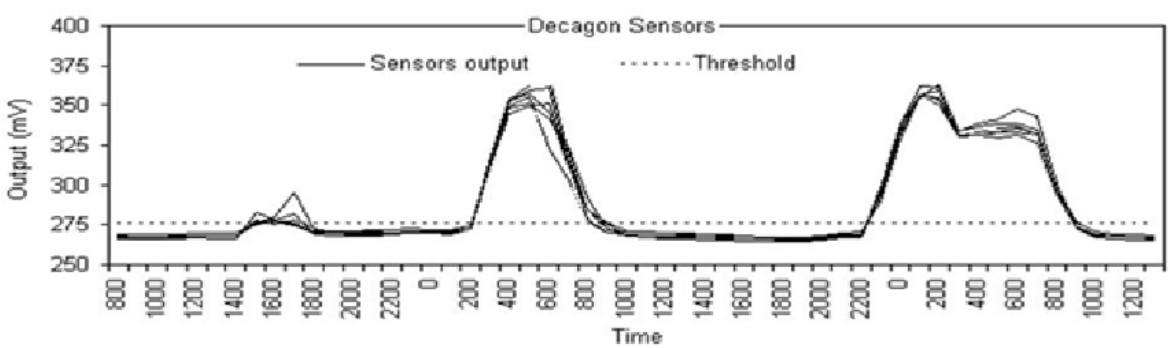

Figure 3-3. Typical LWS-L response at 2.5 VDC excitation.

Datalogger

Three CR10X data loggers (Campbell Scientific Inc., Logan, UT) were used to scan measurements every 15 seconds that were averaged for every 15 minutes. Twelve sensors were connected to each data logger in every tree. This data logger model has a very low power requirement, which allowed us to use a 12 VCD solar panel as a power source. The CR10X data logger produced a 2.5 VCD excitation with approximately 10 millisecond duration. It provides short excitation pulses, leaving the probes turned off most of the time, to accomplish the government-specified limits on electromagnetic emissions and to preserve the battery power (Campbell Scientific Inc., Logan, UT).

The LWD was determined by programming the data logger to accumulate time of wetness every 12 hours based on the Boolean threshold. The threshold logger reading for the LWD sensor to be considered wet was $\geq$ 274 mV which were obtained at 2.5 VDC. The 12-hour period started at midnight and ended at noon. The CR10X data logger program is described in Appendix A.

Florida Automated Weather Network station

The Florida Automated Weather Network (FAWN) provides up-to-date weather information through a system of automated weather stations distributed throughout the State of Florida. The Lake Alfred station is located at the UF-CREC facility (28° 06’ N, 81° 42’ W). Two LWS-L sensors were installed at the station; one at 30 cm and the other one at 2 m over turf grass (Figure 3-4). They were placed in a northward leaning position at an inclination of 45 degrees to the horizontal.

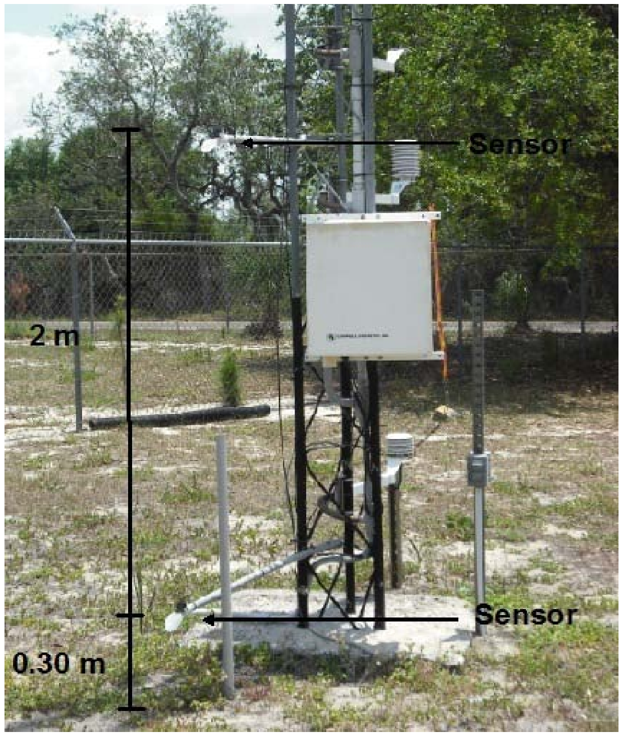

Figure 3-4. FAWN station sensor placement

The data logger averaged the sensors measurements every 15 minutes and the total LWD values for a twelve-hour period were recorded. The database servers maintained by IFAS Information Technologies receive the weather data from the remote station. The information is processed and made available almost instantaneously through the FAWN web server. The LWD for a twelve-hour period of each sensor was downloaded through the FAWN web server for August 2008 and February 2009. These data were used for the regression analysis with the sensors at different positions within the citrus canopy.

Data Analysis

Spatial Variability of LWD

The summer daily data set was partitioned into no rain days and rain days. A rain day was defined as a day with measured rainfall > 0.25 mm (0.01 in). In February 2009, the Pacific Ocean was in 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 where average La Niña rainfall is 30% to 60% less than average (Anonymous, 1990). This La Niña event resulted in below normal rainfall in the peninsula during the winter data collection period and the winter data set did not report any day with rainfall > 0.25 mm with all days being 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). The Glimmix procedure fits statistical models to data with correlations or non constant variability and where the response is not necessarily normally distributed. This procedure is used to analyze repeated measurements, incorporates random effects in the model and so allows for subject-specific (conditional) inference (Glimmix procedure manual, SAS Institute, Inc., Cary, NC). Height and horizontal positions represented the fixed effects. Species were considered as the random effect due to the lack of repetitions within species which would not allow a valid statistical analysis to detect differences among species; but an analysis of variance (ANOVA) revealed that there were no statistical differences 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. This covariance structure specifies a correlation structure within sensors that decreases with increasing lag of time between measurements. Finally, the least squares means 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. In order to eliminate the dew effect during rainy days, 7 rain events during a 12-hour period where the rain stopped during the daytime between 9 am and 3 pm were chosen to assess the hypothesis.

Regression with the Weather Station Sensor

The twelve-hour period LWD at 0.30 m and 2.0 m above turf grass data from the FAWN station was correlated with the data from each sensor at the different twelve positions within the canopy. The SAS corr procedure (SAS Institute, Inc. Cary, NC) was used to compute correlation coefficients between variables using the Fisher two-sided option. Finally, a linear regression analysis was conducted between the FAWN station sensor at 30 cm and 2 m above turf grass with the sensors at the different position within the canopy. The SAS reg procedure (SAS Institute, Inc. Cary, NC) was used to compute a linear regression equation to model the LWD at the canopy using the measurements at the FAWN station.

CHAPTER 4
RESULTS AND DISCUSSION

In this Chapter, the spatial variability of LWD within the canopy as well as the regression results between the LWS-L sensors at the canopy and the sensors at the FAWN weather station will be presented.

Spatial Variability of LWD within the Citrus Canopies

The hypothesis that means LWD at all canopy positions sites were equal was rejected. 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 mean LWD during a 12-hour period (Table 4-1) were detected for height (top, middle and bottom) and horizontal position (west, wc, ec and east). Moreover, there was a marginally significant interaction between height and horizontal position (P =0.0429).

Table 4-1. Generalized Linear Mixed Model (GLMM) type III test for fixed effects of LWD in a 12-hour period

Fixed effects	DF	P value
Height	2	<.0001
Horizontal	3	0.0003
Height*Horizontal	6	0.0429
Season-rain	2	<.0001
Season- rain*Horizontal	4	0.3573
Season- rain*Height	6	0.7041

DF, degrees of freedom

As mentioned in the Chapter 3, the LWD summer data was split in rain and no-rain days while the winter data contained only no-rain days. These variables represent the “season-rain” fixed effect described in Table 4-1. Significant differences (P<.0001) in mean LWD during a 12-hour period were detected for “season-rain” fixed effect. The interaction between the “season-rain” variable with height and horizontal positions was not significant (Table 4-1), which indicates that during the summer and winter seasons, trees have similar patterns of variation in LWD at each height and horizontal position.

The hypothesis that LWD differences tend to be minimized with rainfall events was assessed and the statistical analysis revealed that LWD heterogeneity was significantly different for height even during rainy days (Table 4-2). During rainy days, the wetness was due to rainfall and dew events, so this result includes a combined effect of dew events and rainfall within a rain day. Dew events were reported during late night and early morning, while rainfall periods occurred randomly at daytime and nighttime. Marginal significant differences were detected for horizontal positions (P=0.0404) during rainy days. Significant interactions of height and horizontal positions were observed for winter but not for summer (Table 4-2).

Table 4-2. Generalized Linear Mixed Model (GLMM) type III test for fixed effects by season of LWD in a 12-hour period.

		P value		
		Summer		Winter
Fixed effects	DF	No-rain	Rain	No-rain
Height	2	<.0001	0.001	<.0001
Horizontal	3	0.0033	0.0404	0.0016
Height*Horizontal	6	0.101	0.7363	0.0036

DF, degrees of freedom

All trees had similar daily patterns of longer LWD at the top of the canopy during rain free days; but the LWD variability pattern during rainy days was inconsistent during 45% of the rainy days. These inconsistencies could be caused by the LWD being the result of a combined effect of rainfall and dew events within a rain day and due to the fact that in every day the rain events were reported at different hours of the day, which affected the drying process.

The thermal stratification within a plant canopy varied during the daytime and the nocturnal period (Fig. 4-1). During the daytime, a thermal inversion develops within the canopy layer because the shaded ground surface beneath tends to remain cool, while the mean air temperature profile above a plant canopy is unstable due to the incoming short wave radiation absorbed by the top canopy. During the nocturnal period, the opposite is observed (Jacobs et al., 1992). The mean air temperature profile at top canopy becomes stable due to the loss of long wave radiation (radiative cooling), and thus the unstable lower vegetation layer is capped and thereby decoupled from the above-canopy region (Jacobs et al., 1995). This suggests that the drying pattern within crop canopies could vary depending on the time when the rain stopped. The drying process within the plant is influenced by the micrometeorological conditions of the atmospheric boundary layer.

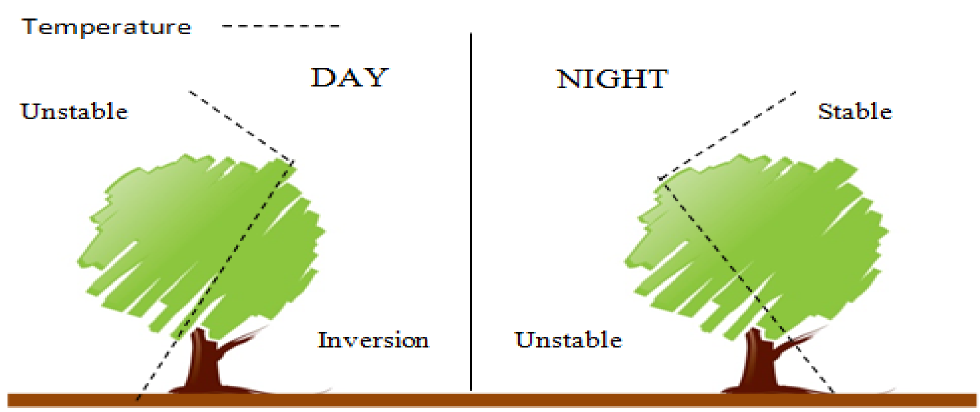

Figure 4-1. Mean air temperature vertical profile within canopy during daytime and nighttime (Adapted from Griffiths, J.F. 1978. Applied climatology an introduction. Second edition. Oxford University Press)

The hypothesis that after a rainfall during daytime, the LWD could be shortest at the top of the canopy, which is more exposed to wind and solar radiation or the LWD differences could be minimized was assessed. In order to eliminate the dew effect during rainy days, 7 rain events during a 12-hour period in which the rain stopped during the daytime between 9 am and 3 pm were chosen to assess the hypothesis. The statistical analysis of 7 rain events in a 12-hour period where the rain stopped during the daytime revealed that there was no significant difference of LWD among heights and horizontal positions (Table 4-3). Thus, the variability of LWD tended to be minimized with rainfall, but the LWD due to dew made the LWD differences among heights during rainy days significant.

Table 4-3. Generalized Linear Mixed Model (GLMM) type III test for fixed effects of LWD during 7 daytime rain events.

Fixed effects	DF	P value
Height	2	0.5288
Horizontal	3	0.5869
Height*Horizontal	6	0.9306

DF, degrees of freedom

Throughout the 7 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 4-4) suggested that the dry-off in the top canopy occurred about 32 minutes before the middle canopy and 16 minutes before the bottom canopy. Leaf wetness lasted longest in the middle canopy.

Table 4-4. Mean LWD of 7 rain events during daytime

Height	Mean LWD (hour)
Top	4.10
Middle	4.64
Bottom	4.36

A possible explanation for longer LWD in the middle canopy discussed by Griffiths (1978) suggests that during the daylight hours the added vertical currents of the thermals can cause an almost independent cell to develop, and at ground level the air may be flowing at 180° to that in the free air above the trees as Fig 4-2 shows below. This wind flow could promote a drying process that starts in the top layer followed by the bottom and finally the middle layer. Jacobs et al. (2005) found in a potato field in the center of the Netherlands that the leaf drying shortly after sunrise starts in the top layer followed by the center and bottom layers because in a potato field the inter row space and the roughness height are smaller than in a citrus grove not allowing a wind cell flow among rows.

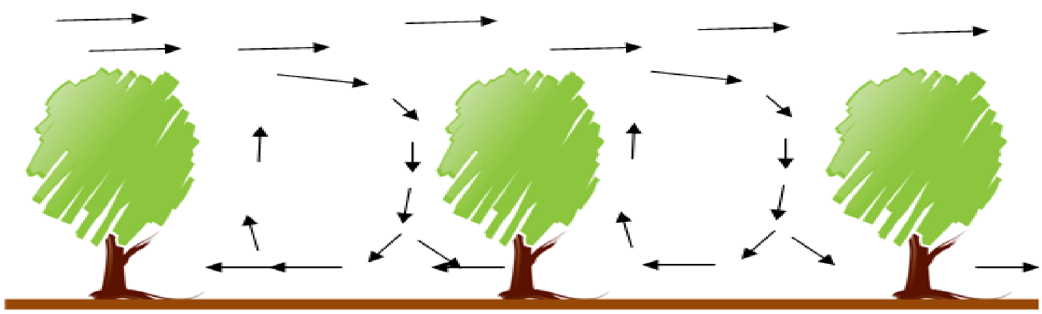

Figure 4-2. Possible schematic wind flow among rows in a citrus grove [Adapted from Griffiths, J.F. 1978. Applied climatology an introduction. Second edition. Oxford University Press.]

Although rain always leads to longer leaf wetness, this parameter cannot be easily predicted from climatologically parameters such as relative humidity or rainfall. The dissipation of leaf wetness is strongly influenced by many factors such as the type of vegetation and the micrometeorological conditions of the atmospheric boundary layer (Kim et al., 2002). The mean daily duration of rainfall for the daytime rain events was 0.9 hours, whereas the average LWD was 4.4 hours, implying that it took on average 3.5 hours to dry the canopy during daytime after rain.

According to our observations, the LWD after nighttime rainfall could last longer than daytime rainfall because during the night, the radiative cooling of the canopy and the weather conditions promote lower evaporation rates compared to those during the daytime.

Least Square Means Multiple Comparisons for Fixed Effects. The LSM multiple comparisons for height showed that the top canopy positions had longer LWDs compared with the middle and bottom canopy positions (Table 4-3 and Figure 4-3). Mean daily LWD at the middle and bottom canopy positions were not significantly different, but were significantly different between the bottom and middle positions and the top canopy position. This pattern was consistent both during the summer and winter seasons. The differences in mean daily LWD between top and bottom for no-rain days (dew) 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. It is important to emphasize that during rainy days the wetness was due to rainfall and dew events, so this result includes a combined effect of dew events and rainfall. Even though the rainfall minimizes the differences of LWD among heights, the LWD variability from dew makes the daily mean LWD differences among heights during the rainy days significant. The east-central and west-central horizontal positions have the longest LWD (Table 4-5), but the differences among horizontal positions were not as pronounced as the differences among heights.

Table 4-5. Daily mean 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	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						
EC	4.5	a	11.6	a	2.2	a
WC	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

Numbers in the same column followed by the same letter are not significant different at the 5% probability level. WC, west-central and EC, east-central.

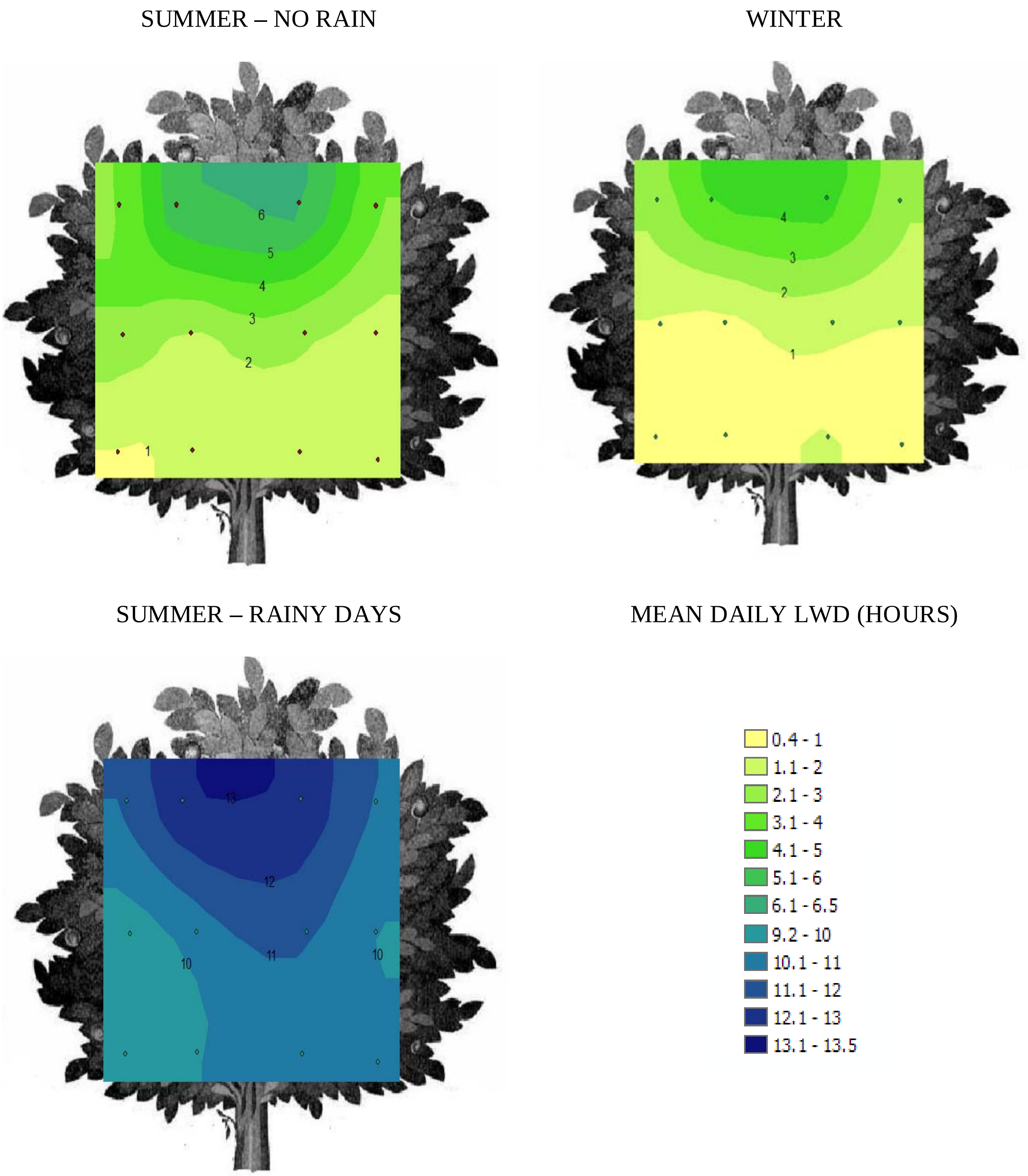

Figure 4-3. Mean daily Leaf Wetness Duration (LWD) in hours. Daily data sets were partitioned into rainy (measured rainfall $\geq$ 0.25 mm) and no-rain days.

The measurements of LWD within citrus canopies in central Florida showed a spatial heterogeneity in height and horizontal position within the canopy. That heterogeneity was significantly different during rainy days and rain-free days, but the differences were more pronounced when wetness was produced by dew rather than rainfall and dew combined.

LWD was significantly longer at the top of the canopy compared to the middle and bottom both during the summer and winter seasons. 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 top of the canopy 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 that height level (Batzer et al., 2008 and 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). Klem et al. (2002) found that the nocturnal radiative cooling of the vegetative surfaces, the lack of thermally driven turbulence, and the stabilization of the boundary layer lead to cooling of the near-surface air causing the condensation of the water vapor on the plant surface. Rain often wets the entire canopy and minimizes the LWD differences among heights; therefore, the longer LWD at the canopy top during rain days was result of dew events during the night and early morning.

Longer LWD at the east-central horizontal positions could be related to the prevalent westerly winds in August 2008 and because the central positions were more exposed to the inter row space which gets more wind allowing a higher radiative heat loss. The differences among horizontal positions were not as pronounced as the differences among heights.

The spatial variability of LWD within the citrus canopy showed that this variable is affected not only by weather conditions, but also by plant structure and height, which affects 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. They demonstrated that LWD at the top of an apple tree canopy averaged about 3 h more per day than the lower western portion of the canopy. Santos et al. (2008) found that coffee plants showed the longest LWD in the lower portions of the canopy; the banana plants had the longest LWD in the upper third of the canopy; whereas for the cotton crop, no difference was observed between the top and lower third of the canopy. Moreover, Sentelhas et al. (2005) found that the LWD was longer at the top in apple and maize crop, whereas for grapes, cultivated in a hedgerow system, and coffee plants the average LWD did not differ between the top and inside canopy.

The spatial heterogeneity of LWD within citrus canopies in central Florida displayed substantial spatial variability in LWD showing that this variable is affected not only by weather conditions but also by plant structure and height, which affects the crop microclimate. These findings emphasize the importance of accounting for the impact of spatial heterogeneity when in canopy measurements of LWD are used as inputs to disease-warning systems. The understanding of the LWD variability within citrus canopies will allow us to improve the performance of disease warning systems that rely on LWD as input.

Spatial Variability of LWD during Winter and Summer

Rain days during the summer season showed higher mean daily LWD compared to no-rain days (Table 4-6). During no-rain days, dew is the main source of wetness and 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 in the winter. Warm air can hold more water vapor because the vapor pressure (Oliver and Hidore, 2002). The average relative humidity in August 2008 was 82% and the dew point temperature was 73°F, whereas in February 2009, average relative humidity was 67% and dew point temperature 47°F. The weather parameter values such as temperature, relative humidity, solar radiation, vapor pressure deficit and rainfall duration per evaluation period can be found in Table 4-7.

Table 4-6. Mean daily LWD (hours) by season and rainfall.

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

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

Table 4-7. Mean hourly weather parameters values per evaluation period: 11 days for summer-no rain, 20 days for summer-rain days and 30 days for winter.

	Summer		Winter
	No-rain days	Rain days	No-rain days
T min (°F)	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
Solar Radiation (w/m^2)	221.1	138.3	190.7
Wind speed (mph)	3.1	4.6	4.7
Rainfall duration (h)	0	1.9	0

Sentelhas et al. (2008) found that LWD can be estimated with acceptable accuracy by RH above a specific threshold (RH>90%). Dew formation depends on the object temperature, the relative humidity and dew point temperature of the surrounding air. When the surface on which deposition takes place is colder than the dew point air temperature, dew is formed.

Longer LWD produced by dew at the top of the canopy should be expected for citrus in humid climates because the dewfall (dew originating 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 Nicole (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 produced by dew could vary according the regional climatic conditions which affect the dewfall and dew-rise processes.

Estimation of Canopy LWD from Sensors over Turf Grass

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 above turf grass showed that the sensor at 0.30 m provided a more accurate estimate of LWD at the top – east central position of the canopy (Fig. 4-4 A). The R^2 coefficient (0.83) of the linear regression between the LWD measurements collected by the sensor at 2.0 m with the LWD data collected at the top-east central position in the canopy showed that there is good agreement between these variables (Fig. 4-4 B); but the sensor at 0.30 m above turf grass have better agreement than the sensor at 2.0 m in estimating LWD at the top-east central position since it has a higher R^2 coefficient (0.92). It should be noted that the top-east central position within the canopy had the longer 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 minutes and an average underestimation of 4.6% by the sensor at the station at 0.30 m over turf grass.

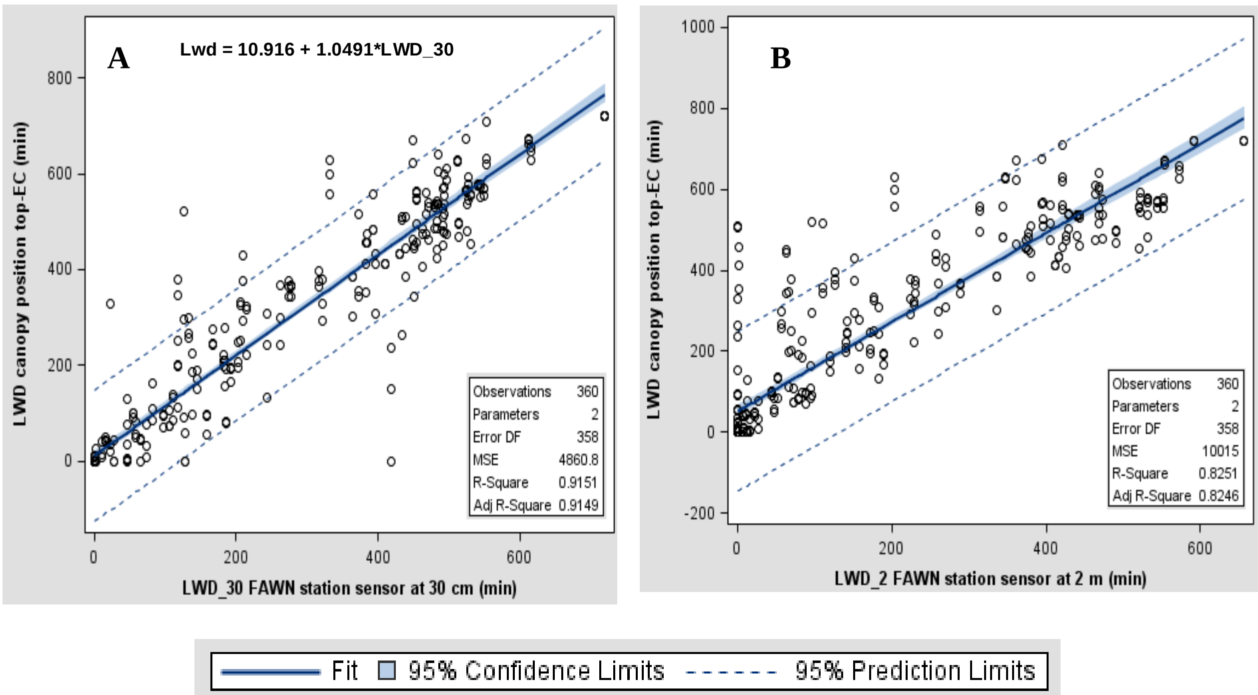

Figure 4-4. Linear regression between LWD measured at the canopy top-EC position and LWD measured at FAWN station sensor at (A) 0.30 m over turf grass (B) 2.0 m over turf grass.

The R^2 coefficients of the linear regression between the LWD measurements collected by the sensors at 0.3 m and 2.0 m with the LWD data collected at the middle (Fig. 4-5 A,B) and bottom (Fig. 4-6 A,B) positions in the canopy showed that there is not a good agreement between these measurements. The sensors over turf grass gave weak estimates of LWD in the middle and bottom canopy positions with a tendency to overestimate LWD. Both precision and accuracy decreased from the top of the canopy to the bottom.

The LWD at the top of the citrus canopy can be accurately estimated from measurements of LWD at the FAWN station sensor at 0.30 m 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 at 0.30 m over turf grass provided quite accurate estimates of LWD at the top canopy but poorer estimates for wetness within the crop canopies. 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 were within 14% (25 min) of the actual wetness duration. These findings imply that measurements at nearby weather stations can be used as substitutes for canopy LWD measurements in disease warning systems which eliminate some mechanical risks and practical considerations related to having sensors within the crop canopy to estimate leaf wetness duration.

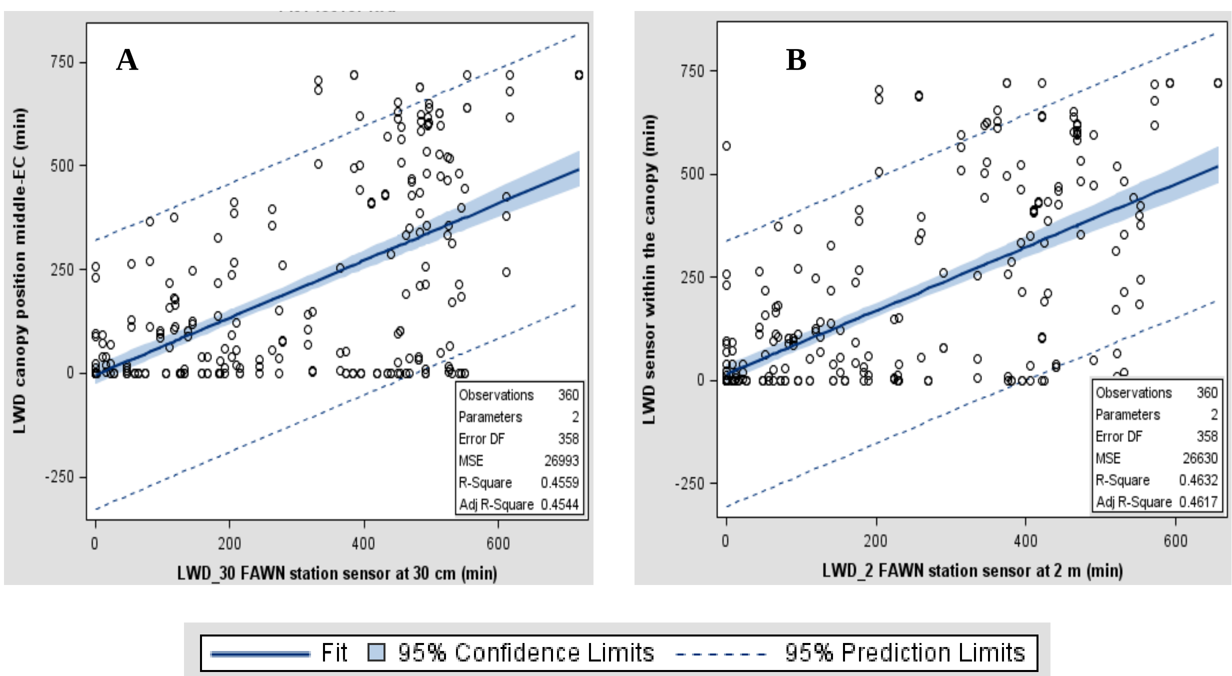

Figure 4-5. Linear regression between LWD measured at the canopy middle-EC position and LWD measured at FAWN station sensor at (A) 0.30 m over turf grass (B) 2.0 m over turf grass.

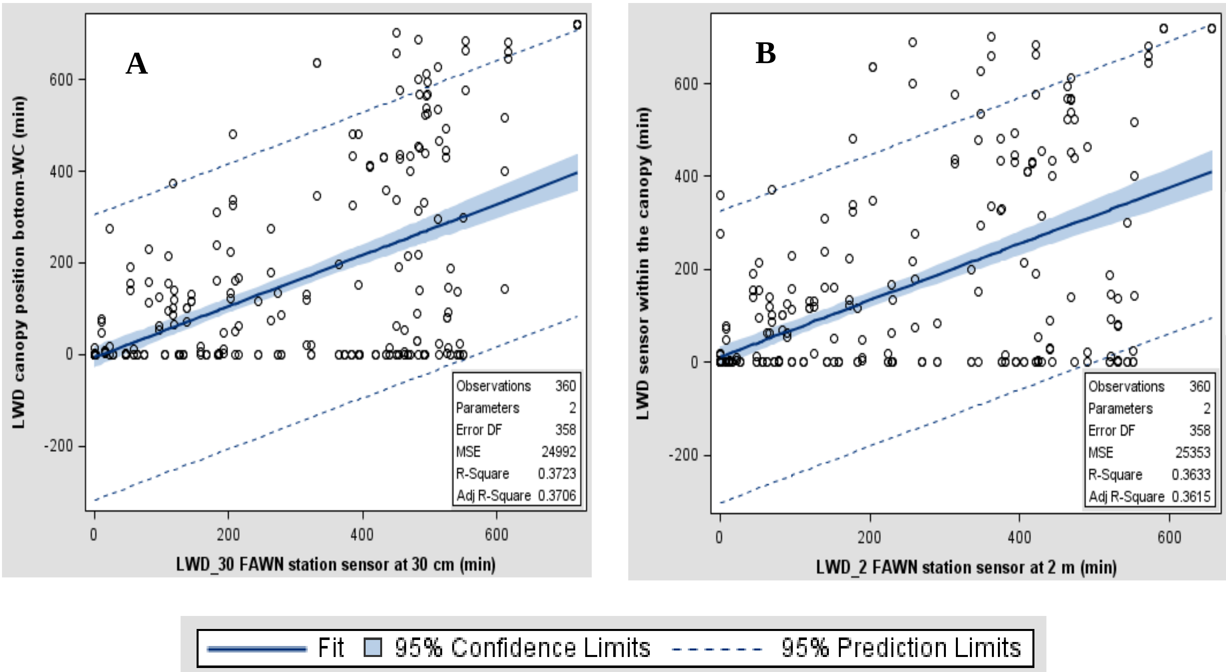

Figure 4-6. Linear regression between LWD measured at the canopy bottom-EC position and LWD measured at FAWN station sensor at (A) 0.30 m over turf grass (B) 2.0 m over turf grass

CHAPTER 5
CONCLUSIONS

The measurements of LWD within citrus canopies in central Florida (humid climate) showed spatial heterogeneity in height and horizontal position within the canopy. That heterogeneity showed a constant pattern of longer LWD at the top of the canopy during rain and no-rain days; but the differences were more pronounced when wetness was produced by dew rather than rainfall and dew combined. The top canopy positions have longer LWDs compared to the middle and bottom canopy positions.

Differences in LWD among canopy positions were greatest during no-rain days where the only source of wetness was from dew. Greater dew duration at the top canopy occurs 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 create a barrier that delays the heat loss of the leaves at the middle and bottom canopy. Rain often wets the entire canopy and minimizes the LWD differences among heights; therefore, the longer LWD at the canopy top during rain days was result of dew events during the night and early morning.

Longer LWD were observed, at the east-central horizontal positions , and could be related to the prevalent westerly winds in August 2008 and because the central positions were more exposed to the inter row space. The differences among horizontal positions were not as pronounced as the differences among heights. The spatial variability of LWD within citrus canopies demonstrates that the crop-canopy microclimate influenced by weather factors and the plant structure and height controls the wetness duration, letting different portions of leaves in the canopy become wet (dew) at different times.

LWD produced by dew during the summer was longer than winter. Higher relative humidity and dew point temperature during summer were shown to be the weather conditions responsible for longer mean daily LWD produced by dew. The understanding of the spatial heterogeneity of LWD within citrus canopies will allow us to improve the performance of disease warning systems that relies on LWD as input.

The nearby FAWN weather station leaf wetness sensor at 0.30 m over turf grass provide accurate estimates of LWD at the top of the canopy which have the maximum LWD. These measurements represent a good alternative for an accurate LWD estimation in citrus canopies which allows its use in many operational plant disease management schemes eliminating some mechanical risks and practical considerations related to having sensors within the crop canopy to estimate leaf wetness.

APPENDIX
PROGRAM

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;{CR10X}
;Program for LEAF WETNESS SENDORS - Decagon LWS - 12 sensors
;Dr. Clyde Fraisse
;Programmer - WAYNE WILLIAMS - ABE March 11, 2008

;Sensors 1,2,3,4-a E1, 1,2,3,4-b E2, 1,2,3,4-c E3
*Table 1 Program
 01: 15        Execution Interval (seconds)
1:  Z=F x 10^n (P30)
1: 1        F
2: 00       n, Exponent of 10
3: 50       Z Loc [ site_ID   ]
2:  Excite-Delay (SE) (P4)
1: 4        Reps
2: 5        2500 mV Slow Range
3: 1        SE Channel
4: 1        Excite all reps w/Exchan 1
5: 1        Delay (0.01 sec units)
6: 2500     mV Excitation
7: 1     -- Loc [ LWmV_1a   ]
8: 1.0      Multiplier
9: 0.0      Offset
3:  Beginning of Loop (P87)
1: 0        Delay
2: 4        Loop Count

    4:  Z=F x 10^n (P30)
     1: 0.0      F
     2: 00       n, Exponent of 10
     3: 13    -- Z Loc [ LWMDry_1a ]

    5:  Z=F x 10^n (P30)
     1: 0.0      F
     2: 00       n, Exponent of 10
     3: 17    -- Z Loc [ LWMCon_1a ]

    6:  Z=F x 10^n (P30)
     1: 0.0      F
     2: 00       n, Exponent of 10
     3: 21    -- Z Loc [ LWMWet_1a ]

7:  End (P95)
8:  Beginning of Loop (P87)
1: 0        Delay
```

```
2: 4        Loop Count
   9:  If (X<=>F) (P89)
    1: 1     -- X Loc [ LWmV_1a   ]
    2: 4        <
    3: 274      F
    4: 30       Then Do
       10:  Z=F x 10^n (P30)
        1: .25      F
        2: 00       n, Exponent of 10
        3: 13    -- Z Loc [ LWMDry_1a ]

   11:  Else (P94)
       12:  If (X<=>F) (P89)
        1: 1     -- X Loc [ LWmV_1a   ]
        2: 3        >=
        3: 284      F
        4: 30       Then Do
           13:  Z=F x 10^n (P30)
            1: .25      F
            2: 0        n, Exponent of 10
            3: 21    -- Z Loc [ LWMWet_1a ]

       14:  Else (P94)
           15:  Z=F x 10^n (P30)
            1: .25      F
            2: 00       n, Exponent of 10
            3: 17    -- Z Loc [ LWMCon_1a ]

       16:  End (P95)
   17:  End (P95)

18:  End (P95)

;Sensors 5,6,7,8-b E2
19:  Excite-Delay (SE) (P4)
1: 4        Reps
2: 5        2500 mV Slow Range
3: 5        SE Channel
4: 2        Excite all reps w/Exchan 2
5: 1        Delay (0.01 sec units)
6: 2500     mV Excitation
7: 5     -- Loc [ LWmV_1b   ]
8: 1.0      Multiplier
9: 0.0      Offset
20:  Beginning of Loop (P87)
1: 0        Delay
```

```
2: 4        Loop Count
    21:  Z=F x 10^n (P30)
     1: 0.0      F
     2: 00       n, Exponent of 10
     3: 25    -- Z Loc [ LWMDry_1b ]

    22:  Z=F x 10^n (P30)
     1: 0.0      F
     2: 00       n, Exponent of 10
     3: 29    -- Z Loc [ LWMCon_1b ]

    23:  Z=F x 10^n (P30)
     1: 0.0      F
     2: 0        n, Exponent of 10
     3: 33    -- Z Loc [ LWMWet_1b ]

24:  End (P95)
 25:  Beginning of Loop (P87)
1: 0        Delay
2: 4        Loop Count
    26:  If (X<=>F) (P89)
     1: 5     -- X Loc [ LWmV_1b   ]
     2: 4        <
     3: 274      F
     4: 30       Then Do

        27:  Z=F x 10^n (P30)
         1: .25      F
         2: 00       n, Exponent of 10
         3: 25    -- Z Loc [ LWMDry_1b ]
    28:  Else (P94)
        29:  If (X<=>F) (P89)
         1: 5     -- X Loc [ LWmV_1b   ]
         2: 3        >=
         3: 284      F
         4: 30       Then Do

            30:  Z=F x 10^n (P30)
             1: .25      F
             2: 00       n, Exponent of 10
             3: 33    -- Z Loc [ LWMWet_1b ]

        31:  Else (P94)
            32:  Z=F x 10^n (P30)
             1: .25      F
             2: 00       n, Exponent of 10
```

```
            3: 29     -- Z Loc [ LWMCon_1b ]
         33:  End (P95)
     34:  End (P95)
35:  End (P95)

; Sensors 9,10,11,12-c E3
36:  Excite-Delay (SE) (P4)
1: 4        Reps
2: 5        2500 mV Slow Range
3: 9        SE Channel
4: 3        Excite all reps w/Exchan 3
5: 1        Delay (0.01 sec units)
6: 2500     mV Excitation
7: 9     -- Loc [ LWmV_1c   ]
8: 1.0      Multiplier
9: 0.0      Offset

37:  Beginning of Loop (P87)
1: 0        Delay
2: 4        Loop Count
     38:  Z=F x 10^n (P30)
      1: 0.0      F
      2: 00       n, Exponent of 10
      3: 37    -- Z Loc [ LWMDry_1c ]
     39:  Z=F x 10^n (P30)
      1: 0.0      F
      2: 00       n, Exponent of 10
      3: 41    -- Z Loc [ LWMCon_1c ]
     40:  Z=F x 10^n (P30)
      1: 0.0      F
      2: 00       n, Exponent of 10
      3: 45    -- Z Loc [ LWMWet_1c ]
41:  End (P95)

42:  Beginning of Loop (P87)
1: 0        Delay
2: 4        Loop Count
43:  If (X<=>F) (P89)
1: 9     -- X Loc [ LWmV_1c   ]
2: 4        <
3: 274      F
4: 30       Then Do
     44:  Z=F x 10^n (P30)
      1: .25      F
      2: 00       n, Exponent of 10
      3: 37    -- Z Loc [ LWMDry_1c ]
```

```
45:  Else (P94)
   46:  If (X<=>F) (P89)
    1: 9     -- X Loc [ LWmV_1c   ]
    2: 3        >=
    3: 284      F
    4: 30       Then Do

       47:  Z=F x 10^n (P30)
        1: .25      F
        2: 00       n, Exponent of 10
        3: 45    -- Z Loc [ LWMWet_1c ]

   48:  Else (P94)
       49:  Z=F x 10^n (P30)
        1: .25      F
        2: 00       n, Exponent of 10
        3: 41    -- Z Loc [ LWMCon_1c ]
   50:  End (P95)
51:  End (P95)
52:  End (P95)
53:  If time is (P92)
1: 0        Minutes (Seconds --) into a
2: 15       Interval (same units as above)
3: 10       Set Output Flag High (Flag 0)
54:  Real Time (P77)^11868
1: 110      Day,Hour/Minute (midnight = 0000)
55:  Sample (P70)^15613
1: 1        Reps
2: 50       Loc [ site_ID   ]
56:  Average (P71)^8669
1: 4        Reps
2: 1        Loc [ LWmV_1a   ]
57:  Average (P71)^1681
1: 4        Reps
2: 5        Loc [ LWmV_1b   ]
58:  Average (P71)^25562
1: 4        Reps
2: 9        Loc [ LWmV_1c   ]

59:  If time is (P92)
1: 0        Minutes (Seconds --) into a
2: 720      Interval (same units as above)
3: 10       Set Output Flag High (Flag 0)
60:  Sample (P70)^18967
1: 1        Reps
```

```
2: 50       Loc [ site_ID   ]
61:  Totalize (P72)^26743
1: 12       Reps
2: 13       Loc [ LWMDry_1a ]
62:  Totalize (P72)^9415
1: 12       Reps
2: 25       Loc [ LWMDry_1b ]
63:  Totalize (P72)^164
1: 12       Reps
2: 37       Loc [ LWMDry_1c ]

*Table 2 Program
 02: 0.0000    Execution Interval (seconds)
*Table 3 Subroutines
End Program

-Input Locations-
1 LWmV_1a   5 3 1
2 LWmV_2a   9 1 1
3 LWmV_3a   9 1 1
4 LWmV_4a   17 1 1
5 LWmV_1b   5 3 1
6 LWmV_2b   9 1 1
7 LWmV_3b   9 1 1
8 LWmV_4b   17 1 1
9 LWmV_1c   5 3 1
10 LWmV_2c   9 1 1
11 LWmV_3c   9 1 1
12 LWmV_4c   17 1 1
13 LWMDry_1a 1 1 2
14 LWMDry_2a 1 1 0
15 LWMDry_3a 1 1 0
16 LWMDry_4a 1 1 0
17 LWMCon_1a 1 1 2
18 LWMCon_2a 1 1 0
19 LWMCon_3a 1 1 1
20 LWMCon_4a 1 1 0
21 LWMWet_1a 1 1 2
22 LWMWet_2a 1 1 0
23 LWMWet_3a 1 1 0
24 LWMWet_4a 1 1 0
25 LWMDry_1b 1 1 2
26 LWMDry_2b 1 1 0
27 LWMDry_3b 1 1 0
28 LWMDry_4b 1 1 0
29 LWMCon_1b 1 1 2
```

30 LWMCon_2b 1 1 0
31 LWMCon_3b 1 1 0
32 LWMCon_4b 1 1 0
33 LWMWet_1b 1 1 2
34 LWMWet_2b 1 1 0
35 LWMWet_3b 1 1 0
36 LWMWet_4b 1 1 0
37 LWMDry_1c 1 1 2
38 LWMDry_2c 1 1 0
39 LWMDry_3c 1 1 0
40 LWMDry_4c 1 1 0
41 LWMCon_1c 1 1 2
42 LWMCon_2c 1 1 0
43 LWMCon_3c 1 1 0
44 LWMCon_4c 1 1 0
45 LWMWet_1c 1 1 2
46 LWMWet_2c 1 1 0
47 LWMWet_3c 1 1 0
48 LWMWet_4c 1 1 0
50 site_ID 1 2 1
-Program Security-
0000
0000
0000
-Mode 4-
-Final Storage Area 2-
0
-CR10X ID-
0
-CR10X Power Up-
3
-CR10X Compile Setting-
3
-CR10X RS-232 Setting-
-1
-DLD File Labels-
0
-Final Storage Labels-
0,LWmV_1a_AVG~1,8669
0,LWmV_2a_AVG~2
0,LWmV_3a_AVG~3
0,LWmV_4a_AVG~4
1,LWmV_1b_AVG~5,1681
1,LWmV_2b_AVG~6
1,LWmV_3b_AVG~7
1,LWmV_4b_AVG~8

2,LWmV_1c_AVG~9,25562
2,LWmV_2c_AVG~10
2,LWmV_3c_AVG~11
2,LWmV_4c_AVG~12
3,LWMDry_1a_TOT~13,26743
3,LWMDry_2a_TOT~14
3,LWMDry_3a_TOT~15
3,LWMDry_4a_TOT~16
3,LWMCon_1a_TOT~17
3,LWMCon_2a_TOT~18
3,LWMCon_3a_TOT~19
3,LWMCon_4a_TOT~20
3,LWMWet_1a_TOT~21
3,LWMWet_2a_TOT~22
3,LWMWet_3a_TOT~23
3,LWMWet_4a_TOT~24
4,LWMDry_1b_TOT~25,9415
4,LWMDry_2b_TOT~26
4,LWMDry_3b_TOT~27
4,LWMDry_4b_TOT~28
4,LWMCon_1b_TOT~29
4,LWMCon_2b_TOT~30
4,LWMCon_3b_TOT~31
4,LWMCon_4b_TOT~32
4,LWMWet_1b_TOT~33
4,LWMWet_2b_TOT~34
4,LWMWet_3b_TOT~35
4,LWMWet_4b_TOT~36
5,LWMDry_1c_TOT~37,164
5,LWMDry_2c_TOT~38
5,LWMDry_3c_TOT~39
5,LWMDry_4c_TOT~40
5,LWMCon_1c_TOT~41
5,LWMCon_2c_TOT~42
5,LWMCon_3c_TOT~43
5,LWMCon_4c_TOT~44
5,LWMWet_1c_TOT~45
5,LWMWet_2c_TOT~46
5,LWMWet_3c_TOT~47
5,LWMWet_4c_TOT~48
6,Day_RTM,11868
6,Hour_Minute_RTM
7,site_ID~50,15613
8,site_ID~50,18967

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BIOGRAPHICAL SKETCH

Verónica Natalí Santillán-Núñez was born on 1983, in Quito, Ecuador. After graduating from high school in December 2001, she entered to the Zamorano University in Honduras, earning her Bachelor of Science in agricultural science and production in December 2005. She graduated as the second-best student of the Zamorano class of 2005. After her graduation, she worked at Murphy Brown Inc., Waverly, VA, USA, for two years. Murphy Brown is the production group of the pork processing giant Smithfield Foods, is the world's largest hog producer. She acquired experience in swine production and human resources management. Her work was suspended with her desired opportunity to pursue a master's degree. She was offered an assistantship to pursue her graduate education at the Agricultural and Biological Engineering Department at University of Florida, under the supervision of Dr. Clyde Fraisse. She earned a Master of Science degree in December of 2009.