

Paulo C. Sentelhas · Terry J. Gillespie ·
Jean C. Batzer · Mark L. Gleason ·
José Eduardo B. A. Monteiro ·
José Ricardo M. Pezzopane · Mário J. Pedro Jr

Spatial variability of leaf wetness duration in different crop canopies

Received: 28 May 2004 / Revised: 1 January 2005 / Accepted: 16 February 2005 / Published online: 9 March 2005
© ISB 2005

Abstract The spatial variability of leaf wetness duration (LWD) was evaluated in four different height-structure crop canopies: apple, coffee, maize, and grape. LWD measurements were made using painted flat plate, printed-circuit wetness sensors deployed in different positions above and inside the crops, with inclination angles ranging from 30 to 45°. For apple trees, the sensors were installed in 12 east-west positions: 4 at each of the top (3.3 m), middle (2.1 m), and bottom (1.1 m) levels. For young coffee plants (80 cm tall), four sensors were installed close to the leaves at heights of 20, 40, 60, and 80 cm. For the maize and grape crops, LWD sensors were installed in two positions, one just below the canopy top and another inside the canopy. Adjacent to each experiment, LWD was measured above nearby mowed turfgrass with the same kind of flat plate sensor, deployed at 30 cm and between 30 and 45°. We found average LWD varied by canopy position

for apple and maize ($P < 0.05$). In these cases, LWD was longer at the top, particularly when dew was the source of wetness. For grapes, cultivated in a hedgerow system and for young coffee plants, average LWD did not differ between the top and inside the canopy. The comparison by geometric mean regression analysis between crop and turfgrass LWD measurements showed that sensors at 30 cm over turfgrass provided quite accurate estimates of LWD at the top of the crops, despite large differences in crop height and structure, but poorer estimates for wetness within leaf canopies.

Keywords Dew · Rainfall · Microclimate · Plant disease · Warning systems

P. C. Sentelhas (✉)
Agrometeorology Group, Department of Exact Sciences,
ESALQ, University of São Paulo,
P.O. Box 9, 13418-900 Piracicaba, SP, Brazil
e-mail: pcsentel@esalq.usp.br
Tel.: +55-19-34294283
Fax: +55-19-34294439

T. J. Gillespie
Agrometeorology Group, Department of Land Resource
Science, Ontario Agricultural College, University of Guelph,
N1G 2W1,
Guelph, Ontario Canada

J. C. Batzer · M. L. Gleason
Department of Plant Pathology, Iowa State University,
Ames, 50011 IA, USA

J. E. B. A. Monteiro
Agrometeorology Group, Department of Physical Science,
Agricultural College “Luiz de Queiroz”, University of São
Paulo,
P.O. Box 9, 13418-900 Piracicaba, SP, Brazil

J. R. M. Pezzopane · M. J. Pedro Jr
Agrometeorology Group, Agronomic Institute of Campinas,
P.O. Box 28, 13020-902 Campinas, SP, Brazil

Introduction

Crop microclimate is a very important factor in plant disease epidemiology. Leaf wetness duration (LWD), promoted by dew, rainfall, fog, or irrigation, together with air temperature are the two most important micrometeorological factors influencing many phytopathosystems. Consequently, they are used as inputs in many disease-warning systems which advise growers when spraying is really necessary (Huber and Gillespie 1992; Gillespie et al. 1993).

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 (Magarey 1999; Magarey et al. 2001; Madeira et al. 2002). Pest warning systems utilizing LWD inputs must find a way to handle these estimation problems, along with possible within-plant variability. The crop-canopy microclimate is influenced by factors like leaf area, plant structure, planting system or arrangement of the plants in the field, crop height, and others. These factors influence radiation interception and balance, and determine temperature, humidity, and wind regimes within the crop canopy. The microclimatic conditions in turn control wetness duration, allowing various portions of leaves and canopies to become wet and dry at different

times (Monteith and Unsworth 1990; Huber and Gillespie 1992).

Despite considerable effort to develop accurate electronic sensors to measure LWD, there has been little research attention paid to how its variability relates to different cropping situations. Most prior studies of LWD measure this variable at the top of the crop canopy (Wittich 1995; Franc and Panigrahi 1997; Chtioui et al. 1999) or just below (Pedro and Gillespie 1982a, b; Gillespie and Barr 1984; Sentelhas et al. 2004a). While this choice is logical if LWD dynamics are driven by dew, it is unclear how LWD in the canopy interior relates to upper canopy measurements. For example, it is known that LWD inside crop canopies can be longer or shorter than at the top depending on the crop structural characteristics and, consequently, on its microclimate (Monteith and Unsworth 1990).

In general, the microclimate of the canopy interior is often more conducive to disease development than the exterior, but numerous exceptions exist for different kinds of crops, particularly in situations where leaf-surface moisture levels are driven by dew. Pedro (1980), studying LWD in shaded and exposed maize and soybean leaves, observed that wetness was about 1 h longer on shaded leaves for both crops. In contrast, Wittich (1995) observed that LWD was 2 h longer at the top of an apple tree than inside the canopy. Considering these differences, Huber and Gillespie (1992) suggested at least two LWD sensors to monitor wetness spatial variation between top and bottom layers of a canopy.

Based on the above considerations, we designed experiments to investigate the importance of canopy height and type on LWD and to determine whether we could obtain a relationship that could predict crop LWD using only nearby LWD measurements over turfgrass.

Materials and methods

Leaf wetness sensors

Flat, printed-circuit sensors (Model 237, Campbell Scientific, Logan, Utah) were used to measure LWD. These sensors consist of a 1-mm-thick circuit board with interlacing gold-plated copper fingers. Condensation on the sensors lowers the impedance between fingers, which is measured by a datalogger. Each sensor used in this

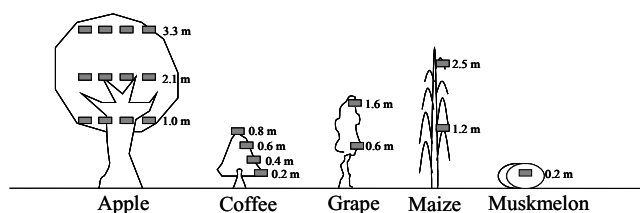


Fig. 1 Schematic representation of the positions of the leaf wetness sensors in each crop studied

study was painted with two or three coats of off-white latex paint, to increase its ability to detect small amounts of wetness, and heat-treated (60–70°C for 12 h) to remove or deactivate hygroscopic components of the paint. The threshold logger reading for each LWD sensor to be considered wet was determined in a laboratory (Kim et al. 2002; Sentelhas et al. 2004b). Values smaller than or equal to this threshold (generally about 9,000 k Ω) were represented by 1 (wet), and greater than it were represented by 0 (dry). Each LWD sensor was mounted on a section of PVC or metal tubing, with inclination angle of 30 or 45° and installed in the field as will be described later.

Field experiments design

The field experiments were conducted on five crops (Fig. 1) at four different locations, representing a wide spectrum of climatic conditions (Table 1). The experiments were not intended to compare between location, therefore the crops were not replicated over location; but the same general method was used at all sites.

At Elora, ON, Canada (43°49' N, 80°35' W), the LWD sensors were installed over mowed turfgrass (~1 ha plot) at 30-cm-height and in two positions within a well-developed maize crop (~1.5 ha), about 200 m NW from the sensors on the turfgrass field, from 28 July to 7 October 2003, totaling 71 days of measurements. In the corn field, an LWD sensor was installed at the height of the upper leaves (moved from 1.8 to 2.5 m as the corn grew), and another inside the canopy at 1.2 m. All LWD sensors were deployed at 30° facing north.

At Ames, Iowa, USA (42°01' N, 93°46' W), LWD sensors were installed over mowed turfgrass at 30-cm-height facing north with an inclination angle of 45°, and in two

Table 1 Average climatic conditions during the period of the experiments in Ames, Iowa, USA (2000, 2001, and 2003), Elora, ON, Canada (2003), Piracicaba, SP, Brazil (2003), and Jundiaí, SP, Brazil

| Place | Period | Year | Ta (°C) | RH (%) | Prec (mm) | Wind ^a (m s ⁻¹) |
|------------------------|-------------|---------|---------|--------|-----------|--|
| Ames, Iowa, USA | 07/21–08/30 | 2000 | 22.2 | 82.5 | 60 | 2.8 |
| Ames, Iowa, USA | 05/30–08/28 | 2001 | 22.4 | 74.9 | 165 | 3.2 |
| Ames, Iowa, USA | 07/23–10/07 | 2003 | 20.5 | 75.1 | 197 | 3.0 |
| Elora, ON, Canada | 07/28–10/07 | 2003 | 16.0 | 83.1 | 344 | 1.8 |
| Piracicaba, SP, Brazil | 10/11–12/22 | 2003 | 18.6 | 65.7 | 45 | 1.4 |
| Jundiaí, SP, Brazil | 10/24–01/14 | 2003/04 | 21.8 | 78.2 | 478 | 1.4 |

^aWind speed was measured at 2 m in Elora, Piracicaba, and Jundiaí, and at 3 m in Ames

(2003/2004), considering data from standard weather stations. (*Ta* = average air temperature, *RH* = average relative humidity, *Prec* = total rainfall, *Wind* = average wind speed)

different crops. One sensor was located just below the top (~20 cm above ground) of a muskmelon canopy (~0.1 ha) at the same angle and orientation, from 23 July to 7 October 2003, totaling 69 days of measurements; and 12 sensors per tree were placed in a semi-dwarf mature apple orchard (~0.8 ha, north-south row orientation, cv. Golden Delicious) in different positions on east-west lines, with an inclination angle of 45° and facing north. Four sensors were located at the top (3.3 m above the ground), four in the middle (2.1 m), and four at the bottom (1.1 m), in three apple trees, from 21 July to 30 August 2000, and in four apple trees, from 30 May to 28 August 2001, totaling 127 days of measurements. Sensors at middle and bottom levels of the apple trees were located inside the leaf canopy.

At Piracicaba, SP, Brazil (22°42' S, 47°30' W), LWD sensors were installed over mowed turfgrass at 30-cm-height and deployed facing south at an inclination angle of 30°, and at four heights in a young coffee plantation (~3 ha, northwest-southeast row orientation, cv. Obatã). Heights of the coffee tree sensors were 20 cm (bottom), 40 cm (middle-low), 60 cm (middle-high), and 80 cm (top), with the sensors at the same 30° angle and south orientation, and close to nearby leaves. The measurements were taken from 11 October to 22 December 2003, totaling 58 days of observations.

At Jundiaí, SP, Brazil (23°06' S, 46°55' W), LWD sensors were installed over mowed turfgrass at 30-cm-height and deployed facing south at an inclination angle of 30°, and at two heights in a grape crop (~0.2 ha, north-south row orientation, cv. Niagara rosada). One sensor was placed at the crop top (160 cm) and another at the bottom (60 cm), both deployed at 30° facing south, from 24 October 2003 to 14 January 2004, totaling 68 days of measurements.

All LWD sensors were connected to dataloggers (models CR10, 21X or CR23X, Campbell Scientific, Logan, Utah) programmed to measure the percentage of the time interval in which the sensors were wet for each 15-(maize and coffee), 20-(grape) or 60-(apple and muskmelon) min period. These differences in the measurement time interval were adopted to agree with the data collected by standard weather stations over turfgrass in these places.

Data analysis

Daily LWD data from the five crops were created by considering 24-h periods that began at noon (12:00) and ended at 11:00 the next day for 60-min data sets, 11:40 for 20-min data sets, and 11:45 for 15-min data sets. For data from apple trees, averages were determined for top, middle, and bottom positions since low variability was observed among the four sensors in each of these three positions for all the trees evaluated (CV = 3.5% for top; CV = 7.5% for middle; and CV = 9.8% for bottom). For muskmelon, a very short crop, a sensor just below the top was considered representative of the top of the canopy. For the melon crop, LWD variability in the canopy was not investigated.

Rainfall was measured at each place using tipping bucket rain gauges installed in nearby standard weather stations.

Daily LWD was additionally labeled with an index indicating whether more than 1 mm of rainfall occurred, and data sets were partitioned into days with wetness caused by dew (dew days) and days with wetness caused by both dew and rain. Data for each crop and location were analyzed using a two-way ANOVA with plant (replicate) and canopy position in order to detect differences among the LWD averages between different positions in the crops, except for muskmelon.

Finally, LWD data obtained over mowed turfgrass (30 cm) were correlated, by geometric mean regression (GMR), also known as the reduced major method (McArdle 1988), with crop LWD data obtained at several positions in the canopies for all five crops. For grass-to-crop LWD comparisons, mean difference (MD) and mean absolute difference (MAD) were also determined.

Results and discussion

When examining both rain and rain-free days, we found a significant effect of canopy position on average LWD for apple and maize crops. The LWD decreased from 8.67 h for the top to 6.78 h for the bottom of an apple tree and from 14.5 h for the top to 13.53 h inside the maize canopy. For the other crops, no significant differences among LWD averages due to canopy position were observed. These differences in LWD variability patterns among crops are associated not only with the distinct plant structures but also with the planting system, crop age, and crop management. In a mature orchard, and in a well-developed maize field, only the top of the canopy is directly exposed to the sky and is generally the first to exhibit wetness, both during dew and rain events. The difference between the LWD at the top and the bottom of the canopy was around 2 h for apple trees, which agreed with results of Wittich (1995). For maize, LWD at the top of the canopy was 1 h longer than inside. Pedro (1980), studying LWD in a maize crop, reported a similar LWD difference between exposed and shaded leaves near the top of the canopy, with shaded leaves having longer LWD than exposed leaves.

In contrast to results for apple and maize, LWD in a young coffee plantation did not vary significantly from the top to the bottom of the canopy. However, even with no statistical difference among position inside the canopy, a tendency for increased in LWD from the top to the bottom was observed. The reason for this opposite behavior in relation to apple and maize canopies is associated with the conical shape of the coffee plant (Fig. 1), which exposes leaves at all levels to the sky and promotes the beginning of wetness almost simultaneously in all plant positions. During the morning, however, the top of the plants is expected to receive more total solar radiation and stronger wind than the other positions, resulting in a more rapid dry-off and hence a shorter LWD. For the conditions of this study, LWD in coffee plants was approximately 1.5 h longer at the bottom than at the top.

For grapes, cultivated in a north-south hedgerow system, LWD did not differ significantly between the top and inside

Table 2 Average leaf wetness duration (LWD, hours) for different positions in apple, coffee, maize and grape canopies, considering both dew and rain days. Numbers in the same line followed by the same letter are not significantly different at the 5% probability level

| Crop | Canopy position | | | | | |
|---------------------|-----------------|--------|-------------|------------|--------|---------|
| | Top | Middle | Middle-high | Middle-low | Bottom | Inside |
| Apple ($n^a=127$) | 8.67 a | 8.25 a | | | 6.78 b | |
| Coffee ($n=58$) | 7.84 a | | 8.50 a | 8.63 a | 9.29 a | |
| Corn ($n=67$) | 14.50 a | | | | | 13.53 b |
| Grape ($n=68$) | 8.48 a | | | | 8.33 a | |

^a Number of days with LWD measurements

Table 3 Average leaf wetness duration (LWD, hours) for different positions in apple, coffee, corn and grape canopies, considering only days with wetness caused by dew. Numbers in the same line followed by the same letter are not significantly different at the 5% probability level

| Crop | Canopy position | | | | | |
|--------------------|-----------------|--------|-------------|------------|--------|---------|
| | Top | Middle | Middle-high | Middle-low | Bottom | Inside |
| Apple ($n^a=90$) | 8.32 a | 7.79 a | | | 6.14 b | |
| Coffee ($n=36$) | 5.06 a | | 5.64 a | 6.16 a | 6.65 a | |
| Corn ($n=43$) | 13.05 a | | | | | 11.23 b |
| Grape ($n=44$) | 6.34 a | | | | 5.88 a | |

^a n Number of dew days with LWD measurements

the canopy. Plant structure associated with the hedgerow planting system probably allowed all sensors to cool approximately at the same rate during the night. During the morning, as well, there was sufficient space between rows that all the sensors received about the same influence of sunshine and wind. The difference observed between top and bottom averages for this study was only 9 min, with an average LWD of 8.48 h at the top and 8.33 h at the bottom.

When only dew days were considered for comparison, similar patterns of average LWD differences among different positions were observed for all crops (Table 3). For rainy days (Table 4), however, some of these patterns changed markedly. Rain often wets the entire canopy, especially when it is intense or occurs for several hours. For apple trees, no significant difference was observed between top and middle positions during rainy days, but at the bottom the average LWD still was 1 h less than at the other positions. For coffee plants, average LWD at the top and the bottom of the canopy was not significantly different from average LWD obtained at the middle-high and middle-low positions. For maize and grape canopies under rain conditions, no differences were observed between average LWD at the top and inside the crops. For maize, this is a change from the pattern observed previously (Tables 2 and 3), but for grape the same pattern was observed for rain, dew, or rain and dew days combined.

Table 4 Average leaf wetness duration (LWD, hours) for different positions in apple, coffee, corn and grape canopies, considering only days with rain. Numbers in the same line followed by the same letter are not significantly different at the 5% probability level

| Crop | Canopy position | | | | | |
|--------------------|-----------------|--------|------------|-------------|---------|---------|
| | Top | Middle | Middle-low | Middle-high | Bottom | Inside |
| Apple ($n^a=36$) | 9.55 a | 9.38 a | | | 8.39 a | |
| Coffee ($n=22$) | 12.39 a | | 13.18 a | 12.66 a | 13.62 a | |
| Corn ($n=24$) | 16.99 a | | | | | 17.43 a |
| Grape ($n=24$) | 12.41 a | | | | 12.83 a | |

^a n Number of rain days with LWD measurements

The comparison of daily LWD measurements using GMR analysis between crop and a “standard” condition at 30 cm over turfgrass (Sentelhas et al. 2004b) showed that the nearby LWD sensors provided reasonably accurate estimates of LWD at the top of the canopies, despite large differences in crop height and structure, but less accurate estimates for wetness within leaf canopies, where other factors such as shading from sun and wind affect wetness onset and drying.

Figure 2 presents relationships between crop and turf sensors for apple trees. Both precision and accuracy decreased from the top of the canopy to the bottom. For the top of the apple trees, the slope of the regression was approximately 0.97 and the intercept -0.42 , representing an average overestimation of 8% by the turf sensor. This average overestimation increased to 13% for the LWD measured in the middle of the apple canopy and to 38% at the bottom. This tendency toward overestimation is also shown by the mean differences presented in Table 5. From the top to the bottom, MD increased from 0.68 to 2.56 h and MAD from 1.51 to 2.93 h.

For coffee plants, the same trend with relation to accuracy and precision was observed (Fig. 3, Table 5), with an average underestimation of 10% of LWD at the top of the canopy, 17 to 18% in the middle, and 24% at the bottom.

For apple and coffee crops, there is a very interesting trend in the intercepts while the slope is approximately constant (between 0.947 and 1.033). The intercept moves

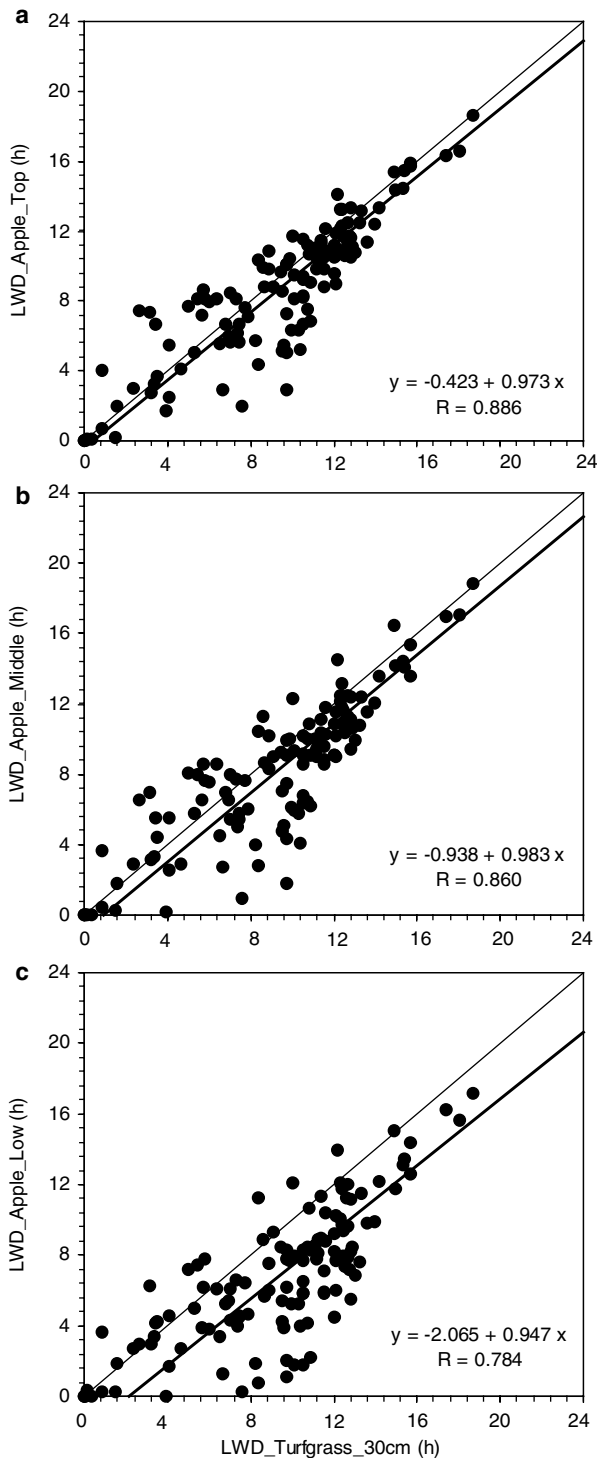


Fig. 2 Relationship between the LWD measured at the top (a), in the middle (b), and at the bottom (c) of the apple trees and at 30 cm over turfgrass, in Ames, Iowa, USA

from near zero at the top to -2 and $+2$ h at the bottom, for apple and coffee crops respectively (Figs. 2 and 3). This suggests that a correction factor could be used to predict crop LWD at the different levels in these two crops from a turf sensor.

Table 5 Mean (MD) and mean absolute (MAD) differences (hours) between leaf wetness duration measured by a standard sensor (over turfgrass at 30 cm) and measured in different crop canopies

| Crop | Canopy position | | | | | |
|-----------|-----------------|--------|-------------|------------|--------|--------|
| | Top | Middle | Middle-high | Middle-low | Bottom | Inside |
| Apple | | | | | | |
| MD | 0.68 | 1.10 | | | 2.56 | |
| MAD | 1.51 | 1.84 | | | 2.93 | |
| Coffee | | | | | | |
| MD | -0.76 | | -1.41 | -1.53 | -2.19 | |
| MAD | 1.25 | | 1.77 | 1.94 | 2.31 | |
| Corn | | | | | | |
| MD | -0.50 | | | | | 0.47 |
| MAD | 0.83 | | | | | 1.67 |
| Grape | | | | | | |
| MD | 0.47 | | | | 0.62 | |
| MAD | 0.92 | | | | 2.65 | |
| Muskmelon | | | | | | |
| MD | -0.60 | | | | | |
| MAD | 1.58 | | | | | |

For the maize crop (Fig. 4, Table 5), the correlation between LWD at the top of the canopy and in the standard condition over turf was similar to that for the coffee canopy, with a 3% average underestimation. The same was observed for the relationship between LWD in the muskmelon crop and over turfgrass (Fig. 5, Table 5), with an average underestimation of 4%. Inside the maize canopy, the average overestimation was 3%, but with more dispersion ($r=0.88$) than that for the relationship at the top ($r=0.97$).

Finally, for the grape canopy (Fig. 6, Table 5), the correlation between crop and turfgrass LWD showed an average overestimation of approximately 6–7% for both the top and bottom of the canopy. However, the dispersion increased considerably at the bottom of the canopy, with $r=0.82$ against 0.98 for the top of the crop, showing that other factors not influencing the turf sensor were affecting the wetness in the lower grape canopy.

For maize and grape crops, the turf LWD sensor was able to predict crop LWD at the top of the canopies quite well. However, the prediction of crop LWD inside the canopy of these crops from the turf sensor showed a tendency toward overestimation up to about 15 h of wetness and of underestimation for LWD >15 h (Figs. 4 and 6). Such behavior does not allow the use of a simple crop correction factor for estimating crop LWD inside the canopy. In this case, a more complex model is required.

Results presented above revealed that upper canopy positions in the homogeneous crops, maize and muskmelon, had greater LWD than the turfgrass sensor. On the other hand, the heterogeneous apple orchard and hedgerow grapes had smaller LWD than the standard turf condition. This opposite behavior may be associated in part with distinct surface cooling processes that happen in these two different crop structures. For continuous crops, the radiative cooling process for the leaves just below the canopy

Fig. 3 Relationship between the LWD measured at the top (a), in the middle (b,c), and at the bottom (d) of the coffee plant and at 30 cm over turfgrass, in Piracicaba, SP, Brazil

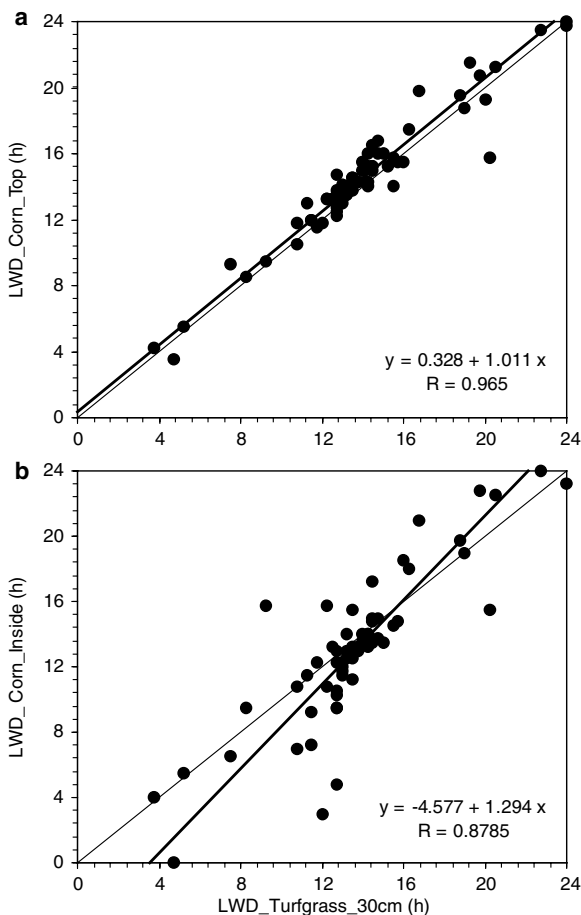
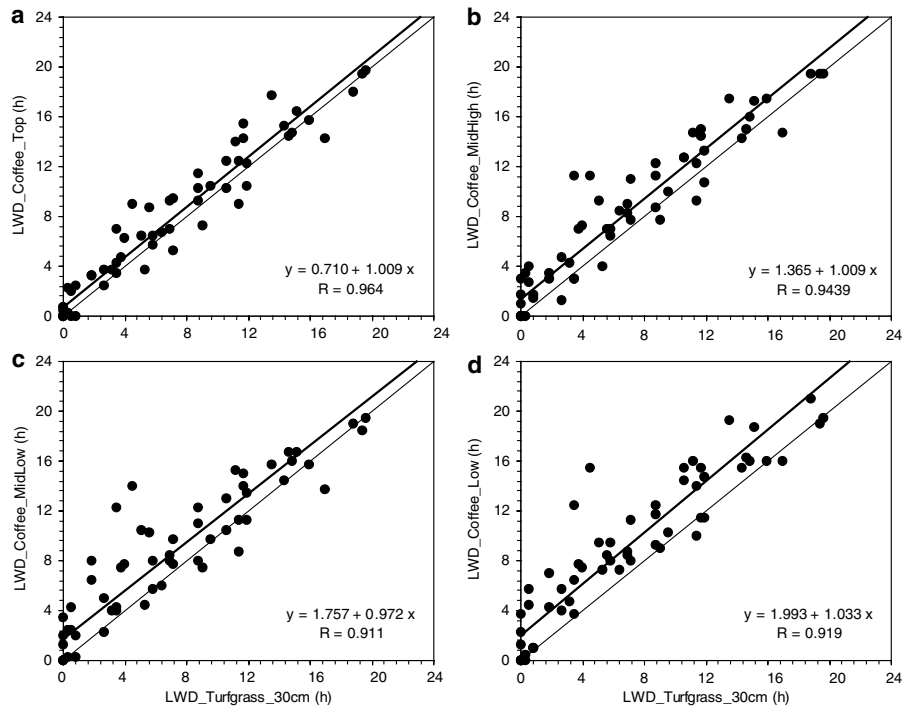


Fig. 4 Relationship between the LWD measured at the top (a) and inside (b) of the corn crop canopy and at 30 cm over turfgrass, in Elora, ON, Canada

top is as fast as over turfgrass, but as the reference sensor was at 30 cm above turfgrass, some delay in dew deposition caused by greater exposure to the wind is expected, resulting in a shorter LWD. For discontinuous crops, surface cooling may be more retarded by incoming turbulent convective heat transfer, which depends on the canopy roughness. In this case, wetness in heterogeneous crops would usually start later, and enhanced transport would allow the wet period to finish earlier than in the turfgrass field. Based on this argument, the underestimation observed for coffee would not be expected since it is a discontinuous crop. However, for this study we used a very young coffee plantation where plants were only 80-cm-tall, approaching a continuous crop in its ability to generate turbulence.

Few studies in the literature have tried to correlate LWD over turfgrass in a weather station with LWD data in adjacent crops, especially at several positions in the canopies. On the other hand, the most accurate and precise physically based models for LWD estimates, like Pedro and Gillespie (1982a, b), Zhang and Gillespie (1990), Gleason et al. (1994), Rao et al. (1998), and Magarey (1999), use standard weather station data. The strong correlations obtained in this study between LWD at 30 cm over turfgrass and the top of the crop canopies reinforce the idea that adopting physically based models to estimate LWD at height of 30 cm over turfgrass (e.g., Madeira et al. 2002; Sentelhas et al. 2004b) is a viable alternative to estimate crop LWD. However, this procedure is only operationally applicable to estimate the LWD at the top of the crops. If this position is associated with largest LWD in the canopy, or little difference in LWD occurs at different canopy positions as observed in this study for apples, maize, and grapes; the procedure of estimating crop LWD

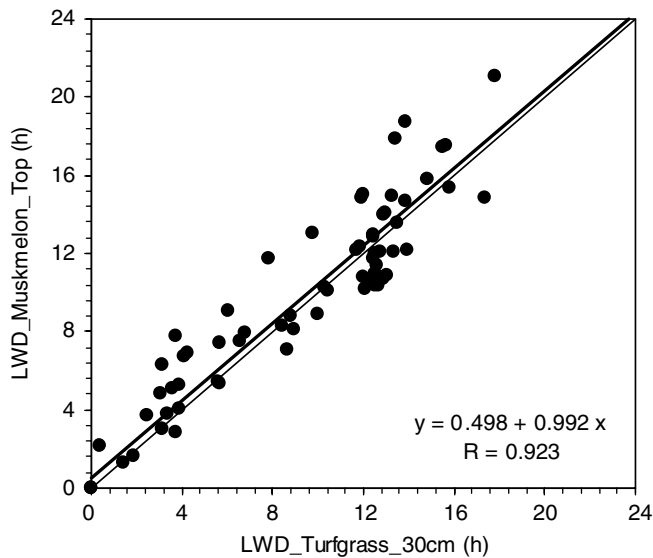


Fig. 5 Relationship between the LWD measured just below the top of the muskmelon crop canopy and at 30 cm over turfgrass, in Ames, Iowa, USA

from a standard weather station measurement or model of LWD becomes very useful. In this case, a small empirical crop correction could be used to adjust the standard LWD measurement to estimate crop LWD, since this variable seems to be dependent on crop structure. On the other hand, if the LWD is greater inside the canopy, this will require the use of site-specific LWD sensors, or a more substantial empirical correction to the standard estimate, or a more complex model. If measurements are made in a crop, this study supports the recommendation of Huber and Gillespie (1992) to use at least two LWD sensors to monitor wetness spatial variation between top and bottom layers of a canopy when the purpose is to run a disease-warning system.

Conclusions

The measurement of LWD in different crops and at different positions inside several crop canopies showed that this variable is affected not only by weather conditions but also by plant structure, architecture, and height, which affect the crop microclimate. The pattern of LWD variation inside the crops differed according to the characteristics mentioned above. For mature apple orchards and for tall mature annual crops like corn, where only the tops of the canopies are directly exposed to the sky, LWD caused by dew was longer at the top than inside the canopies. For young coffee plants and a very well ventilated grape crop in a hedgerow system, no significant differences were observed on dew or rain days for LWD between top and inside positions. On the other hand, during rainy days LWD showed less variation between top and inside positions for apple and maize crops. The use of LWD measured over turfgrass as an estimator of LWD at the top of the crops was a very good option for crops that have maximum LWD at this canopy position or have little variation of LWD at different canopy positions.

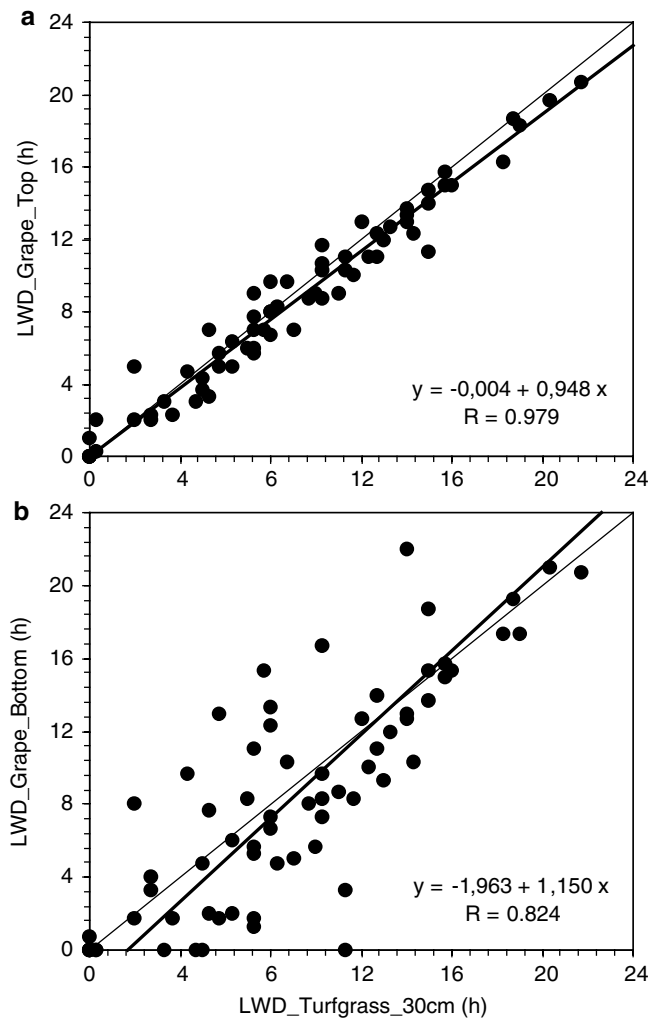


Fig. 6 Relationship between the LWD measured at the top (a) and at the bottom (b) of the grape crop canopy and at 30 cm over turfgrass, in Jundiá, SP, Brazil

The mean absolute errors associated with such estimations are between 0.83 h (50 min) and 1.58 h (95 min), which are small enough to allow use in many operational plant disease management schemes (Magarey 1999). Small, empirical, crop-specific corrections could be used to further reduce these errors.

Acknowledgements This project was funded in part by a fellowship to the first author from CNPq, a Brazilian Government Institution (Proc. 202536/02-5), and by the United States Department of Agriculture. The first and sixth authors are supported by a fellowship from CNPq and the fourth and fifth from FAPESP. The authors wish to thank two anonymous reviewers for their constructive criticism and helpful comments. The experiments of this project comply with current laws of the Brazilian, Canadian, and American Governments

References

- Chtioui Y, Panigrahi S, Francel L (1999) A generalized regression neural network and its application for leaf wetness prediction to forecast plant disease. *Chem Intel Lab Syst* 48:47–58

- Francl LJ, Panigrahi S (1997) Artificial neural network models of wheat leaf wetness. *Agric For Meteorol* 88:57–65
- Gillespie TJ, Barr A (1984) Adaptation of a dew estimation scheme to a new crop and site. *Agric For Meteorol* 31:289–295
- Gillespie TJ, Srivastava B, Pitblado RE (1993) Using operational weather data to schedule fungicide sprays on tomatoes in southern Ontario, Canada. *J Appl Meteorol* 32:567–573
- Gleason ML, Taylor SE, Loughin TM, Joehler KJ (1994) Development and validation of an empirical model to estimate the duration of dew periods. *Plant Dis* 78:1011–1016
- Huber L, Gillespie TJ (1992) Modeling leaf wetness in relation to plant disease epidemiology. *Annu Rev Phytopathol* 30:553–577
- Kim KS, Taylor SE, Gleason ML, Koehler KJ (2002) Model to enhance site-specific estimation of leaf wetness duration. *Plant Dis* 86:179–185
- Madeira AC, Kim KS, Taylor SE, Gleason ML (2002) A simple cloud-based energy balance model to estimate dew. *Agric For Meteorol* 111:55–63
- Magarey RD (1999) A theoretical standard for estimation of surface wetness duration in grape. PhD dissertation, Cornell University, Ithaca, N.Y., USA
- Magarey RD, Seem RC, Russo JM, Zack JW, Waight KT, Travis JW, Oudemans PV (2001) Site-specific weather information without on-site sensors. *Plant Dis* 85:1216–1226
- McArdle BH (1988) The structural relationship: regression in biology. *Can J Zool* 66:2329–2339
- Monteith JL, Unsworth MH (1990) Principles of environmental physics, 2nd edn. Edward Arnold, New York
- Pedro MJ (1980) Relation of leaf surface wetness duration to meteorological parameters. PhD dissertation, University of Guelph, Guelph, ON, Canada
- Pedro MJ, Gillespie TJ (1982a) Estimating dew duration. I. Utilizing micrometeorological data. *Agric Meteorol* 25:283–296
- Pedro MJ, Gillespie TJ (1982b) Estimating dew duration. II. Utilizing standard weather station data. *Agric Meteorol* 25:297–310
- Rao PS, Gillespie TJ, Schaafsma AW (1998) Estimating wetness duration on maize ears from meteorological observations. *Can J Soil Sci* 78:149–154
- Sentelhas PC, Monteiro JEBA, Gillespie TJ (2004a) Electronic leaf wetness duration sensor: why it should be painted. *Int J Biometeorol* 48:202–205
- Sentelhas PC, Gillespie TJ, Gleason ML, Monteiro JEBA, Helland ST (2004b) Operational exposure of leaf wetness sensors. *Agric For Meteorol* 126:59–72
- Wittich K-P (1995) Some remarks on dew duration on top of an orchard. *Agric For Meteorol* 72:167–180
- Zhang Y, Gillespie TJ (1990) Estimating maximum droplet wetness duration on crops from nearby weather station data. *Agric For Meteorol* 51:145–158