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ORIGINAL ARTICLE

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Electronic leaf wetness duration sensor: why it should be painted

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Abstract The purpose of this study was to compare and evaluate the performance of electronic leaf wetness duration (LWD) sensors in measuring LWD in a cotton crop canopy when unpainted and painted sensors were used. LWD was measured with flat, printed-circuit wetness sensors, and the data were divided into two periods of 24 days: from 18 December 2001 to 10 January 2002, when the sensors were unpainted, and from 20 January to 13 February 2002, when the sensors were painted with white latex paint (two coats of paint). The data analysis included evaluating the coefficient of variation (CV%) among the six sensors for each day, and the relationship between the measured LWD (mean for the six sensors) and the number of hours with dew point depression under 2 °C, used as an indicator of dew presence. The results showed that the painting markedly reduced the CV% values. For the unpainted sensors the CV% was on average 67% against 9% for painted sensors. For the days without rainfall this reduction was greater. Comparing the sensor measurements to another estimator of LWD, in this case the number of hours with dew point depression under 2 °C, it was also observed that painting improved not only the precision of the sensors but also their sensitivity, because it increases the ability of the sensor to detect and measure the wetness promoted by small water droplets.

Keywords Dew · Leaf wetness · Plant disease · Sensor · Relative humidity

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Introduction

Leaf wetness duration (LWD), promoted by dew, rainfall, fog, or irrigation, is one of the most important factors influencing the outbreak and severity of plant disease, since the presence of condensation on plant surfaces provides the free water required by the pathogen to germinate and grow. This parameter is used as an input in many disease warning systems (Huber and Gillespie 1992; Kim et al. 2002), which makes the use of fungicide sprays more rational, as presented by Gillespie et al. (1993).

Measurement of leaf wetness is often problematic. According to Magarey (1999) and Madeira et al. (2002), LWD is a difficult variable to measure and cannot be considered a true atmospheric variable as it is related to structural and optical surface properties and microclimate. However, the use of sensors to measure LWD is a good option when they are available, since estimations by empirical or physical models require several meteorological variables and sometimes are too complex.

The sensors used to measure LWD may be classified in three groups (Gillespie and Kidd 1978; Getz 1991): static leaf wetness instruments, which give only an indication of wet or dry conditions; mechanical leaf wetness instruments, which record the change in sensor length, size or weight caused by dew deposition; and electronic leaf wetness instruments that promote a change in sensor impedance.

With the expansion of the governmental and non-governmental automatic weather station networks around the world and more specifically in Brazil, the use of electronic sensors – normally flat, printed-circuit wetness sensors – has increased. However, their use requires attention to some details to produce accurate data, such as shape, size, angle of deployment, orientation, calibration, number of sensors, and painting (Gillespie and Kidd 1978; Gillespie and Duan 1987; Armstrong et al. 1993; Wei et al. 1995; Lau et al. 2000; Miranda et al. 2000; Madeira et al. 2002).

The shape and size of sensors normally depend on the characteristics of the plant and this will affect the indicated period of wetness (Wei et al. 1995). Gillespie and Duan (1987) compared cylindrical and flat-plate sensors and found that LWD was longer on the flat-plate sensors than on cylinders. These authors recommended that the use of cylindrical sensors to monitor LWD for flat leaves be approached with caution.

According to Lau et al. (2000), the angle of deployment and the orientation have less influence on LWD records than does the paint coating. These authors found that unpainted sensors failed to respond to dew onset in 15.4% and 30.8% of the cases for sensors deployed at 30° and 45° respectively. On the other hand, painted sensors responded during each dew event for all the angles deployed. Gillespie and Kidd (1978) used different colors to paint the mock leaf sensors and verified that those painted with off-white and very light gray gave the best approximation to the drying rate of real leaves, especially in comparison to unpainted sensors. Using the Gillespie and Kidd (1978) recommendations, Pedro Jr. (1980) observed that mock leaf sensors measured the onset of dew with an error of less than 15 min and recorded the ending of dew about 30 minutes later than visual observations on real apple leaves. For corn and soybean leaves the differences were around 15 min both for dew onset and dry-off. According to this author, differences of 15 min between visual observations and the measurements are not significant because of the difficulties related to the measurements, particularly spatial sampling errors.

On the other hand, Wei et al. (1995), working with a wetness sensor (electrical conductivity of a flexible, copper-coated polyamide film) to detect condensation on tomato plants in greenhouses, found different results. These authors verified that a coating of acrylic-based latex yielded unreliable results and that vinyl-acetate-based latex, in several concentrations, always misrepresented the onset and evaporation of dew, giving poor repeatability and reproducibility for this type of sensor. They therefore suggested the use of unpainted sensors.

Based on the above discussion, the purpose of this study was to compare and evaluate the performance of electronic leaf wetness duration sensors (flat, printed-circuit wetness sensors) to measure LWD in a cotton crop canopy, using unpainted and painted sensors.

Materials and methods

The field experiment was carried out during the summer of 2001/2002, from December to March, in an experimental area planted with two cultivars of cotton crop (IAC23 and Coodetec), at the Agricultural College "Luiz de Queiroz" of the University of São Paulo (ESALQ/USP), in Piracicaba, State of São Paulo, Brazil (Latitude: 22°42′S, longitude: 47°30′W, altitude: 546 m above sea level).

Six automatic micro-stations equipped with air temperature, relative humidity, and LWD sensors (Fig. 1) were installed at the top of the cotton canopy. In addition, rainfall and wind speed were measured using, respectively, a Texas Electronics tipping-bucket gauge (model TE525M) and a Met One three-cup anemometer (model 014A). The micro-stations were programmed to measure the variables every 10 s and average them every 15 min using a data acquisition system (Campbell Scientific, model CR23X).

Fig. 1 Micro-station equipped with air temperature, relative humidity, and leaf wetness duration (LWD) sensors at the experimental cotton field

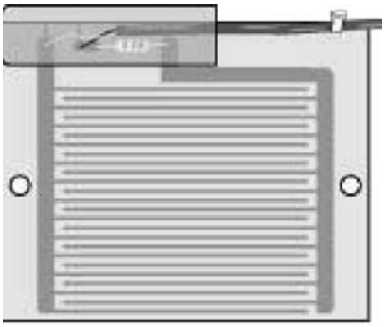

Fig. 2 Campbell Scientific leaf wetness sensor, model 237. (Source: http://www.campbellsci.com/leafwet.html)

LWD was measured with flat, printed-circuit wetness sensors (model 237, Campbell Scientific). Each sensor was mounted on a section of white metal tubing (0.015 m in diameter), angled at 20° to the horizontal (Gillespie and Kidd 1978), and all faced north. This mock leaf consists of a circuit board (1 mm thick) with interlacing gold-plated copper fingers (Fig. 2), as described by Gillespie and Kidd (1978) and Campbell Scientific (1996). Condensation on the sensors lowers the impedance between the fingers, which is measured by the data-logger.

The data were divided in to two periods of 24 days: (a) from 18 December 2001 to 10 January 2002 when the sensors were unpainted, and (b) from 20 January to 13 February 2002 when the sensors were painted with white latex paint (two coats of paint) and heat-treated, as recommended by Gillespie and Duan (1987), to remove hygroscopic components of the paint. The sensors were calibrated before each period to determine the wet/dry transition point. The data analysis included evaluating the coefficient of variation (CV%) among the six sensors for each day:

$$CV\% = (SD/\bar{X}) \times 100$$

where SD is LWD standard deviation, and $\bar{X}$ is the LWD mean value. The relationship (regression analysis) between the measured LWD (mean for the six sensors) and the number of hours with dew point depression (DPD) under 2 °C (NHDPD < 2 °C), an indicator of dew presence, was also used. DPD is given by the difference between air temperature and dew point temperature.

Results and discussion

The coefficients of variation (CV%) for the LWD daily measurements among the six sensors are presented in Fig. 3, where it is possible to see the huge difference between the unpainted and painted sensors. For the period when the sensors were unpainted (Fig. 3a), the daily values of CV% ranged from 2.3% to 139.3%, with an average of 67.4%. In this case, CV% values smaller than 20% occurred only on days with rainfall, indicated by the arrows, when LWD was greater than 15 h. As found by Lau et al. (2000), the unpainted sensors in this study also failed to respond at all during some low-DPD events, which contributed to increased CV%.

For the period when the sensors were painted (Fig. 3b), the CV% values decreased markedly, especially during days with wetness promoted by dew, ranging from 0 to 31.2%, with an average of 9.3%. In this case, the painting increased the sensitivity of the sensors in the detection of small water droplets (Gillespie and Kidd 1978), reducing the underestimation of LWD. For painted sensors the number of coats of paint is another source of variability. Lau et al. (2000), studying sensors with three and nine coats of paint, observed differences both in dew onset and dry-off in comparison to visual observations. According to these authors, three coats gave best results. Gillespie and Kidd (1978) and Pedro Jr. (1980) used two coats, the same number used in the sensors of this study, obtaining good results in comparison to visual observations.

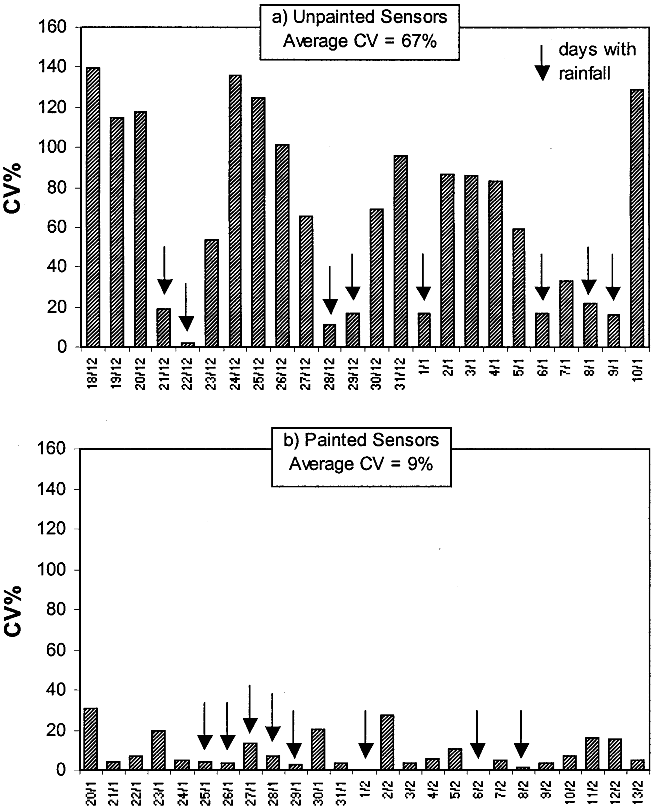

Fig. 3a, b Coefficient of variation (*CV%*) for the LWD measurements made by electronic leaf wetness sensors: unpainted (**a**) and painted (**b**). The *arrows* indicate the days with rainfall

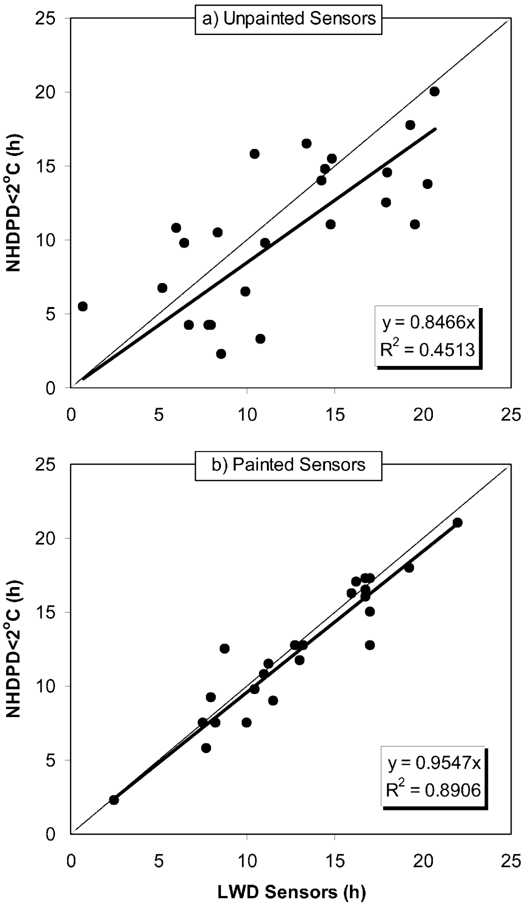

Fig. 4a, b Relationships between the measured LWD (mean for the six sensors) and NHDPD < 2 °C when unpainted (**a**) and painted (**b**) sensors were used

Another way to judge the importance of painting these electronic sensors is by comparing their response to another estimator of LWD. Figure 4 presents the relationship between NHDPD < 2 °C data and sensor measurements of LWD. Statistics of the linear regression forced through the origin are also shown. For the unpainted sensors (Fig. 4a) this relationship resulted in a slope of 0.85, representing an underestimation of about 15%, and in a poor precision (R^2 = 0.45), which was a consequence of high variability among the sensors. On the other hand, when the painted sensors were used (Fig. 4b) the underestimation was equal to 5% (b = 0.95) and the coefficient of determination (R^2), which represents an estimate of the precision, increased to 0.89. In this case, the paint made the measurements more precise because of its ability to spread water and hence to allow a

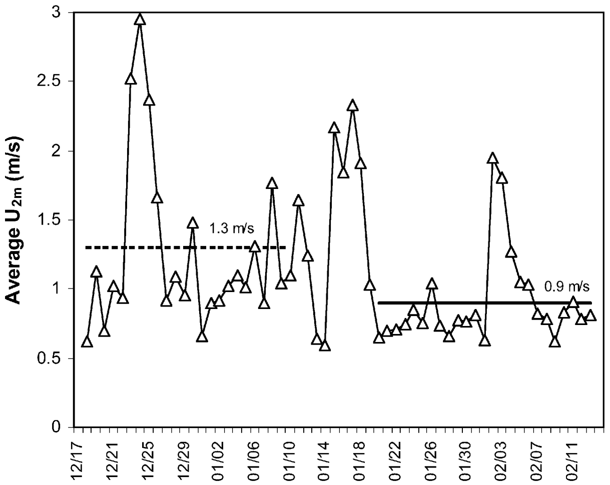

Fig. 5 Average daily wind speed at 2 m over the experimental cotton field. The lines represent the average for the periods when unpainted (*dashed line*) and painted (*solid line*) sensors were used

response of the impedance grid to small amounts of moisture deposited on the painted surface (Gillespie and Kidd 1978). A slight underestimate of LWD by the sensors was observed when compared to the NHDPD < 2 °C criterion (Fig. 4b) but this is expected because dew may not form on a few occasions when DPD is around 2 °C, especially during windy nights, as can be seen in Fig. 5, when dew forms at DPD near zero. However, the use of NHDPD < 2 °C as a LWD estimator is supported by the results found by Gillespie et al. (1993) and Rao et al. (1998) which suggested that estimate of plant wetness duration from simple threshold models based on temperature and relative humidity data were as good as estimates from some complex physical models.

The results presented here, which show an improvement in the sensor performance after painting, agree with the results obtained by Gillespie and Kidd (1978), Pedro Jr. (1980), and Lau et al. (2000). On the other hand, they disagree with those obtained by Wei et al. (1995) in artificial and actual (greenhouse) conditions. The better performance of their unpainted flexible sensor may be related to the size of the electrode gap, which was 0.25 mm against 1 mm in the commercial sensors used in this study and by the other authors cited above. A smaller electrode gap may eliminate the need to paint wetness sensors except when sensor color must be adjusted to match the wetness duration on plant parts whose drying is strongly influenced by solar radiation. Premature sensing of wetness onset and delayed sensing of drying for coated sensors in the study of Wei et al. (1995) may have occurred because they indicate the paint was "air dried". Previously, Gillespie and Duan (1987) reported that drying paint at high temperature is required to avoid early dew onset detection and late drying, presumably because this process removes or deactivates hygroscopic components of the paint.

Conclusions

The results presented in this study of a cotton crop show that electronic leaf wetness duration sensors with a typical electrode spacing of around 1 mm should be painted. This procedure is useful to reduce the underestimation and increase the precision of the measurements. Painting increases the ability of the sensor to detect and measure the wetness promoted by small water droplets and hence reduces the variability among sensors. This study verifies that two coats of paint were enough to reduce the CV% of LWD measurements from 67% to 9% when six sensors were used. This painting procedure is recommended for LWD sensors used in disease warning systems.

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