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Estimating leaf wetness duration on a cotton crop from meteorological data

Estimativa da duração do período de molhamento foliar do algodoeiro a partir de dados meteorológicos

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Abstract *– The purpose of this study was to use and compare four different models to estimate leaf wetness duration (LWD) on cotton leaves, using 15 min data from an automatic weather station installed inside the crop area, and also to show the differences between the LWD measured at 1.7 m in the weather station, and close to the plants. For this purpose, an automatic weather station was installed inside the crop area, where the following meteorological variables were measured at 1.7 m: air temperature and relative humidity, net radiation, wind speed, rainfall, and LWD. Six automatic micro-stations were installed at the top of the crop having sensors of air temperature, relative humidity, and LWD. These meteorological data were used to estimate LWD according to the following methods: Number of Hours with Relative Humidity above 90% (NHRH>90%); Dew Point Depression (DPD); Classification and Regression Tree model (CART); and Aerodynamic Resistance model (RES). The results showed that in general, all methods of LWD estimation performed quite well. For the DPD, CART and RES models an overestimation of around 2%, 6%, and 7% respectively was observed, whereas the NHRH>90% method showed an underestimation of 6%. This analysis resulted in high accuracy of these methods, however the precision of the estimations was not as high, remaining between 0.75 and 0.90, and resulting in mean absolute errors between 1.27 and 2 h. When only dry days were used to estimate LWD a little improvement on accuracy was observed, while for rainy days the precision decreased considerably. Comparing the LWD data obtained in the weather station with those close to the crop canopy, it was verified that a large difference existed between them, mainly for periods with less than 15 to 17 h of wetness. This shows that LWD should be measured or estimated site-specifically, or adjusted by empirical coefficients. For LWD > 17 h, normally promoted by rain, the differences are smaller both between the LWD measured/estimated in the crop and in the weather station, and among the sensors. Therefore the RES model estimated LWD at crop level with high accuracy and regular precision, and is a good option to estimate this variable without the requirement of calibration for each crop and place.*

Key words: *Dew, Leaf Wetness, Plant Disease, Automatic Weather Station and Cotton.*

Resumo *- No presente trabalho teve-se por objetivo empregar e comparar quatro diferentes métodos para a estimativa da duração do período de molhamento (LWD) em folhas do algodoeiro, usando dados provenientes de uma estação automática, em intervalos de 15 min., instalada na área da cultura, e também mostrar as diferenças entre a LWD medida a 1,7 m, na estação meteorológica e próximo das plantas. Para tanto, uma estação automática foi instalada na área da cultura, na qual as seguintes variáveis foram medidas a 1,7 m: temperatura e umidade relativa do ar, saldo de radiação, velocidade do vento, chuva e LWD. Seis microestações foram instaladas, na parte superior da cultura, tendo sensores para a medida da temperatura e umidade relativa do ar e LWD. Esses dados foram usados para se estimar a LWD, de acordo com os seguintes métodos: Número de Horas com Umidade Relativa acima de 90% (NHRH>90%); Depressão do Ponto de Orvalho (DPD); modelo da Árvore de Classificação e Regressão (CART); e modelo da Resistência Aerodinâmica (RES). Os resultados mostraram que, em geral, todos os métodos de estimativa da LWD tiveram boa performance. Para os modelos DPD, CART e RES, foram observadas, respectivamente, superestimativas da ordem de 2%, 6% e 7%, enquanto que, para o método do NHRH>90%, foi observada uma subestimativa da ordem de 6%. Essa análise resultou numa alta acurácia das estimativas feitas por esses métodos, mas apesar disso, a precisão não foi tão elevada, permanecendo entre 0,75 e 0,90, resultando em erros médios absolutos entre 1,27 e 2 h. Quando foram usados somente dias sem chuva para a estimativa de LWD, foi observada uma pequena melhoria na acurácia, enquanto que, para os dias chuvosos, a precisão diminuiu muito. Comparando os dados de LWD obtidos na estação meteorológica, com aqueles obtidos na parte superior da cultura, verificou-se uma grande diferença, especialmente, para os dias com LWD menores que 15 a 17 h. Isso mostra que a medida ou estimativa de LWD deve ser feita, especificamente, para o local e a cultura de interesse ou ajustada por coeficientes empíricos. Para os dias com LWD > 17 h, normalmente causada pelas chuvas, as diferenças entre a LWD na estação e na cultura foram pequenas, o mesmo foi observado entre os sensores utilizados. O modelo RES estimou a LWD ao nível da cultura com alta acurácia e regular precisão, sendo uma boa opção para a estimativa dessa variável sem o requerimento de calibração para cada cultura e local.*

Palavras-chave: *Orvalho, Molhamento foliar, Doenças de Plantas, Estação Meteorológica Automática e Algodão.*

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Introduction

Leaf wetness duration (LWD), promoted by dew, rainfall, fog, or irrigation, is one of the most important factors influencing plant diseases, both their outbreak and severity (HUBER & GILLESPIE, 1992; KIM et al., 2002). Free water over the plant tissue has an important role during many epidemiological processes, mainly affecting infection and sporulation (HUBER & GILLESPIE, 1992). In the cotton crop, LWD and temperature are responsible for the occurrence of several important diseases in the Southeast and Central-West Regions of Brazil (MONTEIRO, 2002).

Measurement of leaf wetness is often difficult (GILLESPIE & KIDD, 1978; MADEIRA et al., 2002), even with the automatic sensors which were developed over the last 35 years. According to KIM et al. (2002), the use of LWD automatic sensors and data-loggers is unattractive to many growers because of the difficulties to install, maintain, and manipulate them, as also described by MONTEIRO el al. (2002). In addition to this fact, the majority of official weather station networks do not have LWD sensors available. So this variable usually must be estimated, especially when the purpose is to use a weather-based plant disease management scheme.

The development of methods to estimate LWD has been the subject of several papers. Many of them are discussed by HUBER & GILLESPIE (1992). They range from the simple empirical methods, based on one or more variables like relative humidity, wind speed and temperature (GLEASON et al., 1994), to the most complex, based on the physical aspects of the dew deposition and evaporation as presented by PEDRO JR. & GILLESPIE (1982a, 1982b), RAO et al. (1998), MAGAREY (1999), and MADEIRA et al. (2002), which use the energy balance and aerodynamic resistance approaches.

Among the empirical methods to estimate LWD the number of hours with relative humidity above 90% (NHRH>90%) is the most common. However, the results presented by the literature have been controversial. GLEASON et al. (1994), comparing LWD measured by wetness sensors and estimated by NHRH>90%, found that the error associated with this empirical method was 40% greater than the error obtained when they used the Classification and Regression Tree Model (CART), which also uses dew point depression (DPD) and wind speed (U) data. Similar results were found by FRANCL & PANIGRAHI (1997) for a wheat crop. On the other hand, RAO et al. (1998) suggested that plant wetness duration estimates from simple threshold models based on RH were as good as estimates from some more complex physical models, when they were tested to estimate LWD in maize ears in Ridgetown, Ontario, Canada. However, these authors emphasize that the models based on physical principles are expected to be transportable from site to site, while the empirical methods need to be tested and validated for each new crop and location.

GILLESPIE & BARR (1984) adapted a physical model, developed by PEDRO JR. & GILLESPIE (1982a, 1982b) to estimate dew duration in apple, corn, and soybeans, to the onion crop and found that this procedure can be transported to a new crop and site to provide practical, useful dew duration estimates for pest management. The same was concluded by RAO et al. (1998) when they used the procedure cited above to estimate LWD in maize ears.

The appropriateness of a particular method of LWD estimation may be dictated by operational factors (RAO et al., 1998), mainly available meteorological data. Therefore the objectives of the present study were to use and compare four models which differed in complexity to estimate wetness duration on cotton leaves, using 15 min data from an automatic weather station installed inside the crop area, and also to show the differences between the LWD measured at 1.7 m in the weather station and close to the plants.

Material and methods

The field experiment was carried out during the summer of 2001/02, from December to March, in an area planted with two cultivars of cotton crop (IAC23 and Coodetec) in Piracicaba, State of São Paulo, Brazil (Lat.: 22°42’S, Long.: 47°30’W, Alt.: 546masl).

An automatic weather station was installed inside the crop area, where the following meteorological variables were measured at 1.7 m: air temperature (T) and relative humidity (RH), net radiation (Rn), wind speed (U), rainfall (R), and LWD (Sensor model 237 – Campbell Sci., painted with two coats of white latex and angled at 20°). Six micro-stations were installed close to the top of the crop, 3 for each cultivar, having sensors of T, RH, and painted LWD. These sensors were adjusted periodically to follow the crop height.

The weather station and the micro-stations were programmed to measure the variables each 10 seconds and average them each 15 min using two automatic data acquisition systems (Campbell Scientific, Models CR10 and CR23X).

These meteorological data were used to estimate LWD according to the following methods:

Number of Hours with Relative Humidity above 90% (NHRH>90%): RH = 90% in the screen was considered as the threshold to dew deposition. The number of 15 min intervals with RH above 90% (N15minRH > 90%) divided by 4 was assumed as hourly LWD:

$$LWD = NHRH > 90\% = \left(\sum_{i=12:15}^{12:00} (N15\min RH > 90\% \right) \Big/ 4 \qquad (1)$$

Dew Point Depression (DPD): the difference between air (T) and dewpoint (Td) temperature has also been suggested as a LWD estimator (GILLESPIE et al., 1993). Duration of wetness is estimated as the length of time that DPD remains between two specific limits. The most satisfactory wetness criteria for the present experiment on cotton were found to be 2.0°C for dew onset and 3.8°C for drying.

Classification and Regression Tree Model (CART): a non-parametric classification procedure suggested by GLEASON et al. (1994), was adapted for 15min data from 12:15 of day 1 to 12:00 of day 2, and to estimate dew duration even during the rainy days (the original method is recommended only for non-rain days). This model was developed to estimate the LWD using DPD, 10-m wind speed and RH in a binary classification tree, consisting of nodes (categories) and branches, to distinguish between wet and dry 15 min periods, as presented in Figure 1, using Equations (2) and (3).

$$(1.6064\sqrt{T} + 0.0036T^2 + 0.1531 RH - \\ + 0.4599 U * DPD - 0.0035 T * RH) > 14.46 \qquad (2)$$

$$(0.7921\sqrt{T} + 0.0046 RH - 2.3889 U - \\ + 0.039 T * U + 1.0613 U * DPD) > 37.00 \qquad (3)$$

The interval of time is classified as wet when the condition in Eq. (2) or (3) is met.

Aerodynamic Resistance Model (RES): as presented by RAO et al. (1998) this method eliminates the requirement for the air temperature measured at the crop level, assuming that the temperature measured above the crop is represented by the weather station data. For this purpose an additional resistance is added above the crop (Figure 2), which is assumed to be the aerodynamic resistance (ra), described by MONTEITH & UNSWORTH (1990) as being:

$$ra = \frac{\ln\left[\dfrac{(z_T - 0.65 z_c)}{0.13 z_c}\right]}{0.4 u*} \qquad (4)$$

where z_c is the crop height (1.0 m), z_T the height of the input temperature (1.7 m), and u* the friction velocity, given by the log wind profile (PEDRO JR. & GILLESPIE, 1982b):

$$u* = \frac{0.4 u_{ZT}}{\ln\left(\dfrac{z_T - 0.65 z_c}{0.13 z_c}\right)} \qquad (5)$$

Using the above relationships, the latent heat flux, LE, for a mock leaf can be estimated for each interval of time using Penman-Monteith approach (MONTEITH & UNSWORTH, 1990):

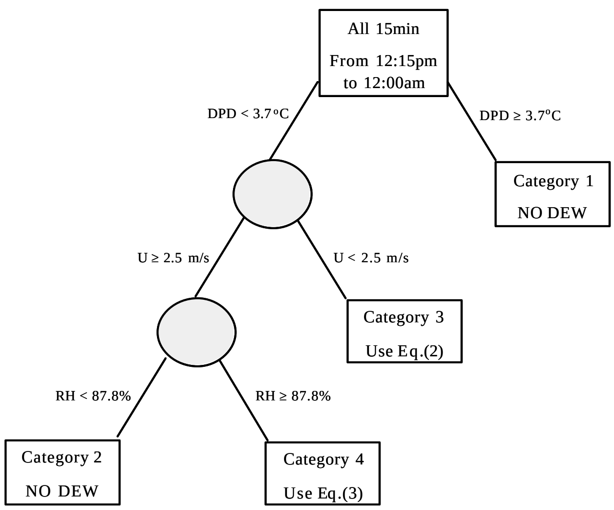

Figure 1. Classification tree, created by the CART procedure, for prediction of leaf wetness duration. Adapted from GLEASON et al. (1994).

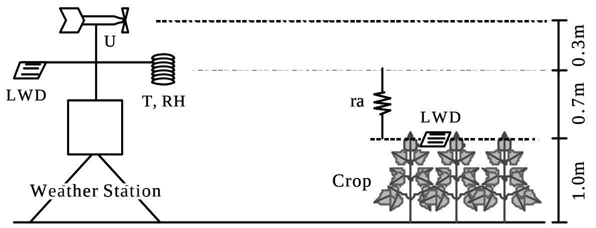

Figure 2. Schematic of the sensor's height and the additional resistance required by the RES model.

$$LE = -\frac{\left[s\,Rn + \dfrac{1200(es_{Ta} - e)}{(ra + rb)}\right]}{(s + g\,*)} \qquad (6)$$

where s is the slope of the saturation vapor pressure curve, es_{Ta} the saturated vapor pressure at the weather station air temperature, e the actual air vapor pressure, γ* the modified psychrometer constant (= $\gamma\, r_V / r_H$), assumed to be 0.64 for dew periods ($r_V = r_H$, two sides of leaf wet), and 1.28 for rainy ones ($r_V = 2\, r_H$, one side of leaf wet), and rb the boundary layer resistance for heat transfer, given by (CAMPBELL & NORMAN, 1998):

$$r_b = \frac{307}{\left(\dfrac{d}{U}\right)^{1/2}} \qquad (7)$$

where d is the effective dimension of the mock leaf (LWD sensor), equal to 0.07 m. The maximum holding capacity of the mock leaf was considered to be 0.8 mm for dew. When there is rainfall, it initiates or increases wetness and is added to the positive LE reservoir up to a value of 0.6 mm. For the LWD estimates at the weather station where the sensor is at the same level as the T and RH sensors (Figure 2), the additional resistance (ra) is not required, then equation (6) can be written as following:

$$LE = -\frac{\left[s\,Rn + \dfrac{1200\,(es_{Ta} - e)}{rb}\right]}{(s + g\,*)} \qquad (8)$$

Following the same procedure adopted by PEDRO JR. & GILLESPIE (1982a), duration of the wetness in this model was inferred as follows: onset occurs when LE > 0 or rain begins, and ending occurs when the condensation and/or rain accumulated by the model is consumed by an equivalent amount of evaporation. The difference between wetness onset and dry-off from 12:15h to 12:00h the next day was defined as LWD for that day.

The estimated and observed LWD data were compared by regression analysis (determination – R^2, and agreement – D coefficients) and by the evaluation of errors (mean error – ME, mean absolute error – MAE, and maximum error – MAX E) as suggested by WILLMOTT et al. (1985), using all data and also by dividing the data into dry and rainy days:

$$D = 1.0 - \left(\frac{\sum_{i=1}^{N}(Oi - Pi)^2}{\sum_{i=1}^{N}\left(\left|Pi - \overline{O}\right| + \left|Oi - \overline{O}\right|\right)^2}\right) \qquad (9)$$

$$ME = \frac{\sum_{i=1}^{N}(Pi - Oi)}{N} \qquad (10)$$

$$MAE = \frac{\sum_{i=1}^{N}\left(\left|Pi - Oi\right|\right)}{N} \qquad (11)$$

$$MAX\ E = \underset{i=1}{\overset{N}{MAX}}\left(Pi - Oi\right) \qquad (12)$$

where: Pi is the estimated LWD, Oi the measured LWD, and O the average measured LWD, all in hours.

Results and discussion

For the all-data set, the relationships among the LWD data measured in the weather station and estimated by the four methods are presented in Figure 3. In general, all methods of LWD estimation performed quite well. For the DPD, CART and RES models (Figure 3b, 3c, and 3d) an overestimation of around 2%, 6%, and 7% respectively was observed, whereas the NHRH>90% method (Figure 3a) showed an underestimation of 6%. This analysis resulted in high values of the agreement index (D), indicating the accuracy of these methods (Table 1). However the precision (R^2) of the estimations was not as high,

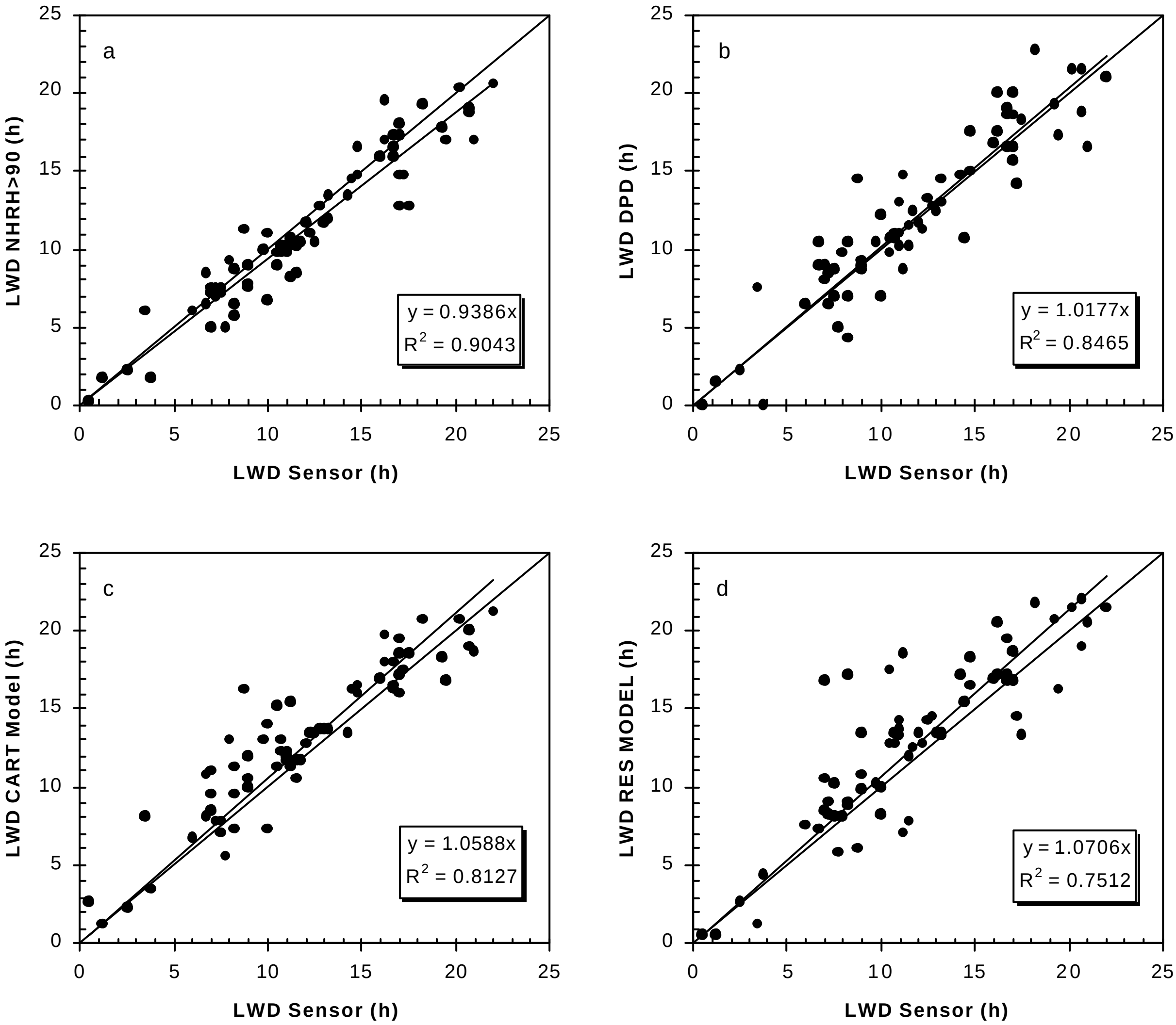

Figure 3. Relationship between LWD measured and estimated by the NHRH>90% (a), DPD (b), CART (c), and RES (d) methods, for meteorological data measured above a cotton crop, during all the period.

remaining between 0.75 and 0.90, and resulting in mean absolute errors between 1.27 and 2 hours. The method that showed the highest precision, NHRH>90%, also presented the lowest maximum error, -4.75 h, followed by DPD (5.75 h), CART (7.5 h) and RES (9.75 h) methods.

The first two methods, NHRH>90% and DPD, being empirical and simple to use, are a practical tool for estimation of LWD in the cotton crop where data of solar or net radiation are generally not available. These two simple methods based on temperature and relative humidity were as good as

Table 1. Regression analysis and errors related to the estimation of LWD by different methods from meteorological data, considering all the period (n = 70 days).

LWD Method	b	R^2	D	ME	MAE	MAX E
					(Hours)	
NHRH>90%	0.94	0.90	0.97	-0.70	1.27	-4.75
DPD	1.02	0.85	0.96	0.32	1.54	5.75
CART	1.06	0.81	0.95	1.07	1.63	7.50
RES	1.07	0.75	0.92	1,11	2.00	9.75

estimates from the other two complex methods, which require net radiation and/or wind speed data. This behavior was also observed by RAO et al. (1998) for the estimation of wetness duration on maize ears, but disagrees with GLEASON et al. (1994) and FRANCL & PANIGRAHI (1997), perhaps due to the dry climate of the midwestern United States. Under this conditions neither 85, 90, 95, nor 100% RH could be used to estimate LWD accurately, and factors as U, cloud cover and soil moisture, must be considered (GLEASON et al., 1984; PEDRO JR. & GILLESPIE, 1980a; WILSON et al., 1999).

When the data set was analyzed considering dry (Figure 4 and Table 2) and rainy days (Figure 5 and Table 3) separately, it was observed that the tendency presented by the models was the same, with underestimation for NHRH>90% and overestimation for the other methods. However, the precision and accuracy of the methods changed. For the dry days (Figure 4 and Table 2), the precision of the estimates made by NHRH>90%, DPD, and CART methods decreased while the accuracy remained practically the same, with underestimation of 7.5% for NHRH>90% and of 1.4% for DPD, and overestimation of 10% for CART. On the other hand, for the RES model an improvement was observed when only dry days were considered. The overestimation fell to 5.3%, and R^2 and D increased respectively to 0.78 and 0.96. For rainy days (Figure 5 and Table 3), few changes were observed in the NHRH>90%, DPD, and CART methods' accuracy but precision was significantly

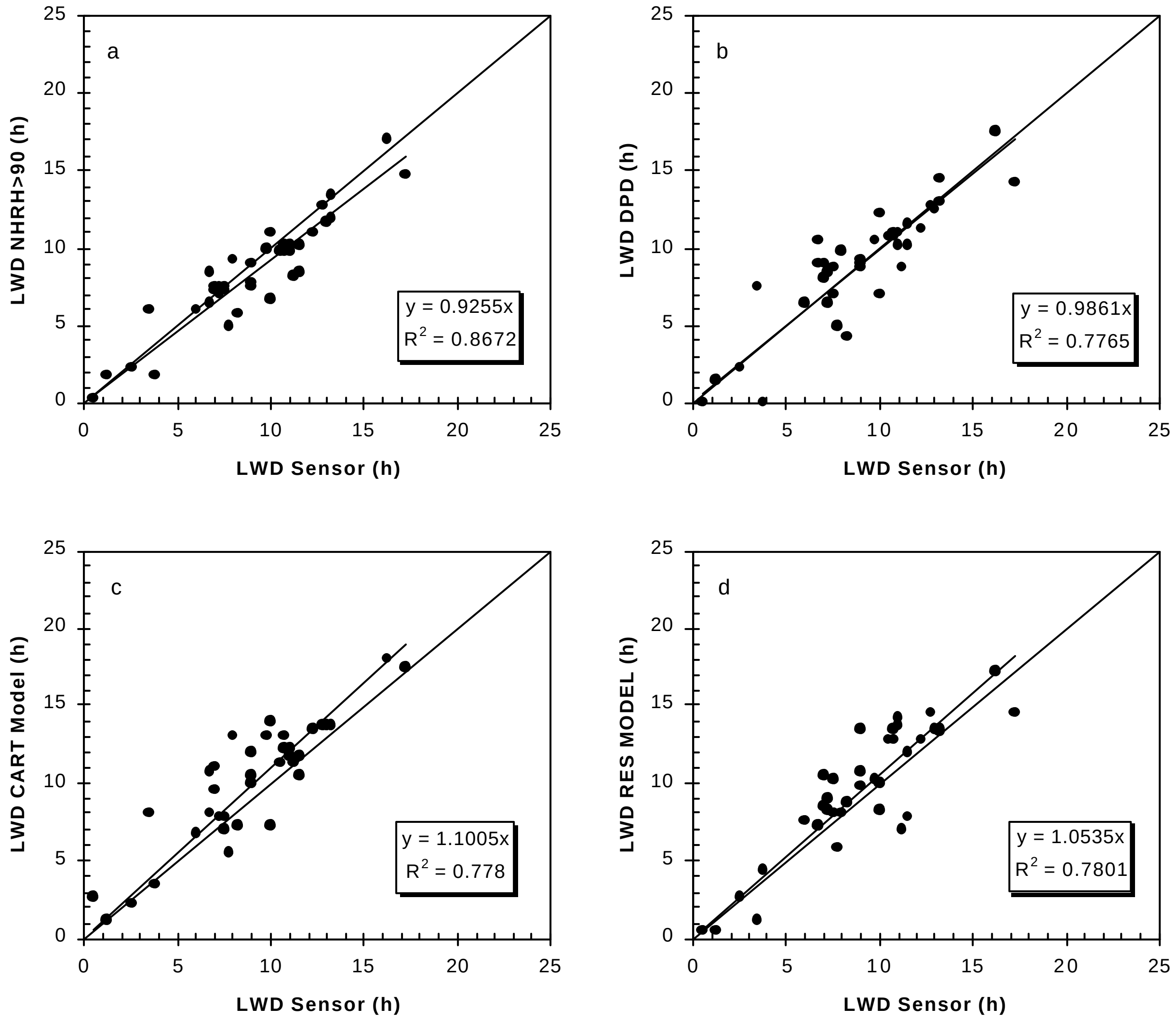

Figure 4. Relationship between LWD measured and estimated by the NHRH>90% (a), DPD (b), CART (c), and RES (d) methods, for meteorological data measured above a cotton crop, during the dry days.

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Table 2. Regression analysis and errors related to the estimation of LWD by different methods from meteorological data, considering only the dry days (n = 38 days).

LWD Method	b	R^2	D	ME	MAE	MAX E
					(Hours)	
NHRH>90%	0.92	0.87	0.98	-0.60	1.09	-3.25
DPD	0.97	0.78	0.96	0.02	1.30	4.00
CART	1.10	0.78	0.95	1.13	1.55	5.00
RES	1.05	0.78	0.96	0,59	1.51	4.50

affected, having R^2 decreased to 0.82, 0.68, and 0.52, respectively. For the RES model, the performance when estimating LWD during rainy days was even worse, especially in relation to the precision (R^2 = 0.11), resulting in a MAE of 2.58 hours and in a MAX E of 9.75 hours. It was observed that the largest errors occurred during nights with high intensity rainfall accompanied by strong wind. During these nights the

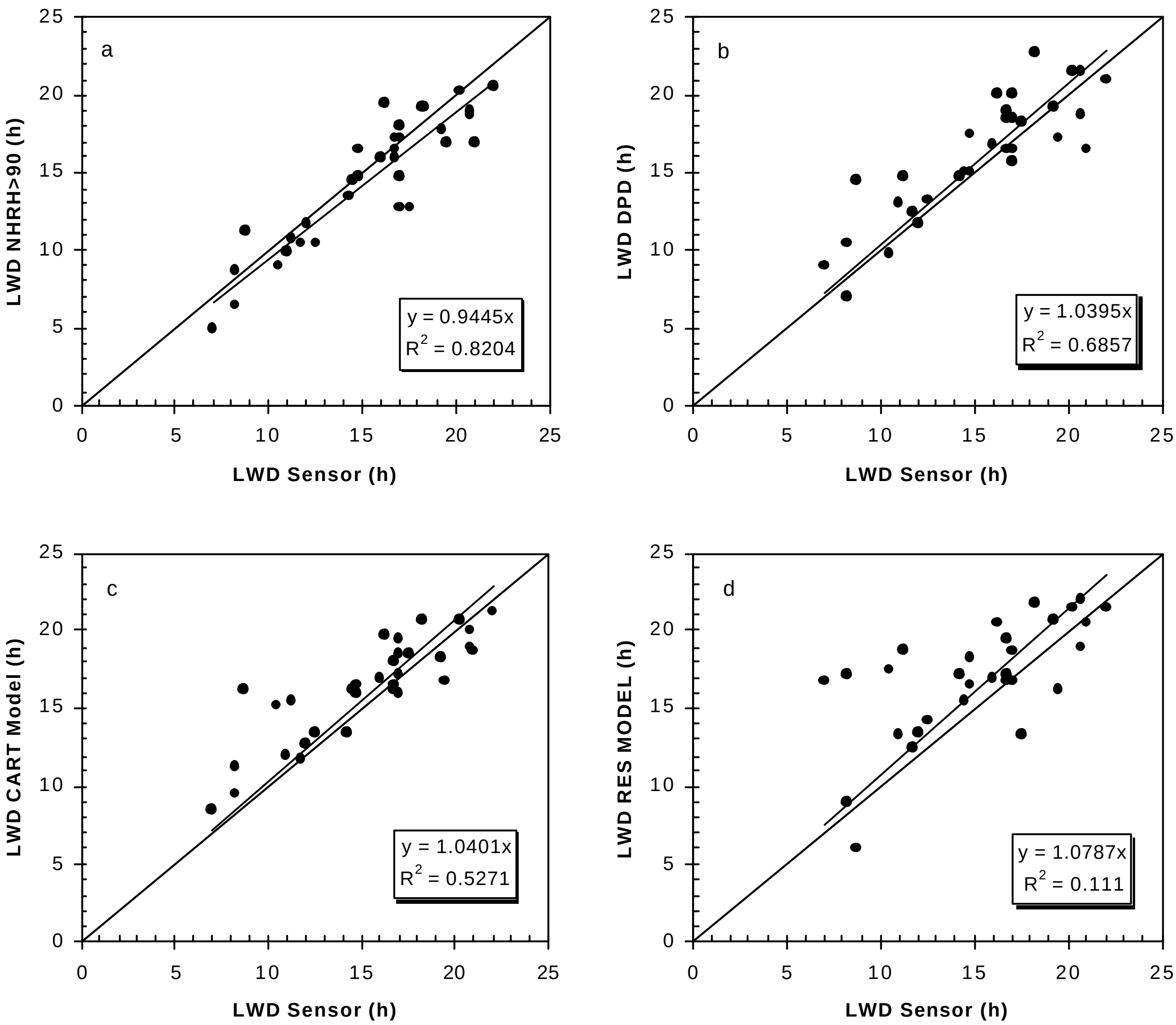

Figure 5. Relationship between LWD measured and estimated by the NHRH>90% (a), DPD (b), CART (c), and RES (d) methods, for meteorological data measured above a cotton crop, during the rainy days.

Table 3. Regression analysis and errors related to the estimation of LWD by different methods from meteorological data, considering only the rainy days (n = 32 days).

LWD Method	b	R^2	D	ME	MAE	MAX E
					(Hours)	
NHRH>90%	0.94	0.82	0.96	-0.80	1.48	-4.75
DPD	1.04	0.68	0.96	0.85	1.73	5.75
CART	1.04	0.52	0.95	1.00	1.73	7.50
RES	1.08	0.11	0.90	1,73	2.58	9.75

RES model showed a long wet period while the sensors became dry.

This decrease in the LWD estimates' precision during rainy days was expected for the CART method since it was developed to work during days without rainfall, as described by GLEASON et al. (1994). On the other hand, it was expected that the RES model would work well under rainy conditions because it considers in its procedure the wetness caused by rainfall. However, even with this bad performance during some rainy days, the errors stayed within the range reported by several authors (GLEASON et al., 1984; RAO et al., 1998; KIM et al., 2002) and obtained by wetness sensors when compared with LWD visual observations (MAGAREY, 1999; MAGAREY et al., 2001). According to MAGAREY (1999) and MAGAREY et al. (2001), LWD sensors have a 95% uncertainty close to 2 h, which suggests that all the LWD estimate methods tested worked as well as direct LWD measurements.

Comparing the LWD data obtained in the weather station above the crop (1.7 m from the ground and, on average, 0.7 m from the top of the canopy) with those observed among the leaves in the crop canopy, it was verified that a large difference existed between them, mainly for periods with less than 15 to 17 h of wetness (Figure 6). This shows that LWD must be measured or estimated site-specifically, or adjusted by empirical coefficients, as those given by the linear regression in Figure 6. For long wetness periods (LWD > 17 h), normally promoted by rain, the differences are smaller both between the LWD measured in the crop and in the weather station, and among the sensors.

To illustrate the use of meteorological methods to estimate LWD at the crop level, the four models were used to compare the LWD estimated with data from the weather station with the LWD estimated with data obtained inside the crop canopy. Figure 7 presents these relationships, which show the same pattern as observed in Figure 6. Among the models, the relationship given by RES model (Figure 7d) is the one that is closest to the measured relationship (Figure 6). This occurs because of the agreement observed between LWD estimated by RES and LWD measured at the crop level, as can be seen in Figure 8. This result gives more confidence about the use of the RES model, a more comprehensive physical model which is transferable to other sites and crops without requirement of local calibrations and supports the hypothesis of rain blow-off from weather station sensor giving bad rain results (Figure 5d).

DPD method also showed to maintain the same relationship presented by the measured data (Figure 7b), but this is a method empirically calibrated and it is not transferable to other crops and sites, as the RES model is.

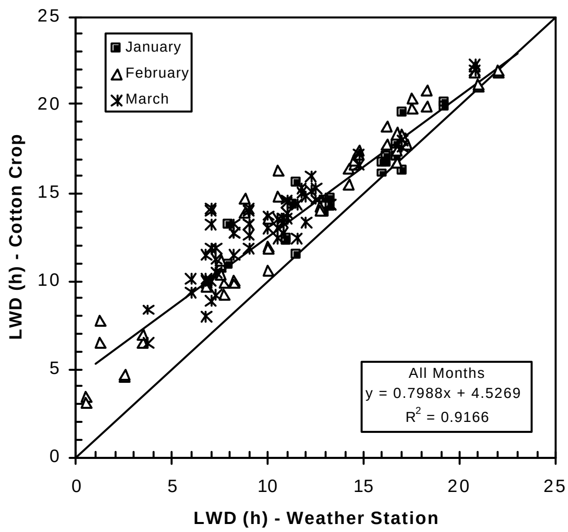

Figure 6. Relationship between LWD measured in the weather station and in the micro-stations, for the cotton crop. Each point for micro-stations is the average of 3 measurements points in each cultivar.

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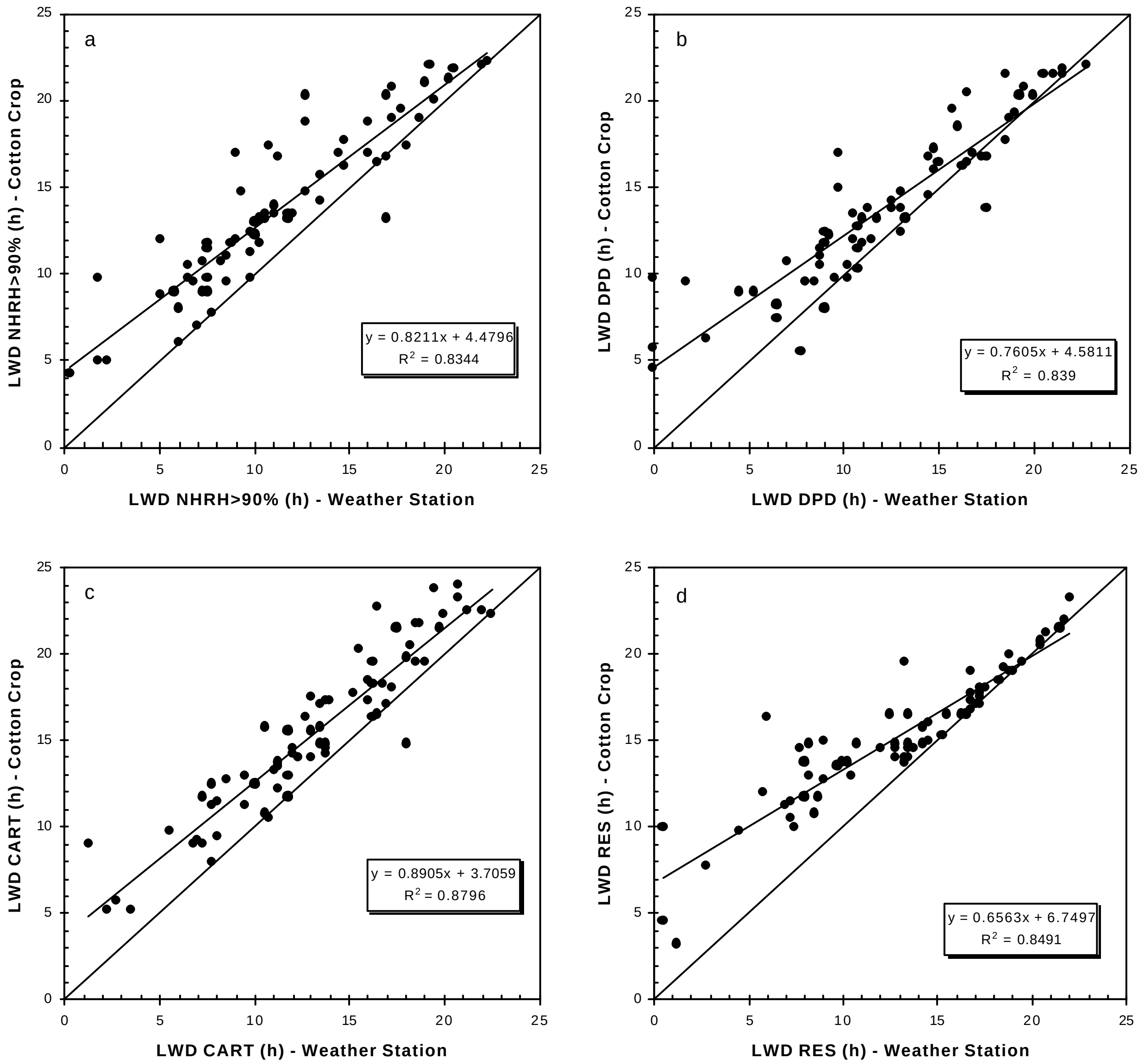

Figure 7. Relationship between LWD estimated by the methods: a) NHRH>90%, b) DPD, c) CART, and d) RES, using data from the weather station and from the micro-stations inside the cotton crop.

Conclusions

The results obtained in this work allow the following conclusions:

a) In general, all methods of LWD estimation performed quite well, presenting small average underestimation for NHRH>90% and overestimation for DPD, CART, and RES.

b) NHRH>90% and DPD methods, being empirical and simple to use, are a practical tool for estimation of LWD in the cotton crop when data of solar radiation and wind speed are not available.

c) All methods presented different performance when used for dry and rainy days, with the worst performance under rainy conditions, especially when accompanied by high wind speed.

d) It was verified that a large difference existed between LWD data obtained in the weather station above the crop and those observed close to the crop canopy, mainly for periods with less than 15 to 17 h of dew.

e) For long wetness periods, normally promoted by rain, the differences between the LWD measured in the crop and in the weather station were small. The same was observed among the sensors.

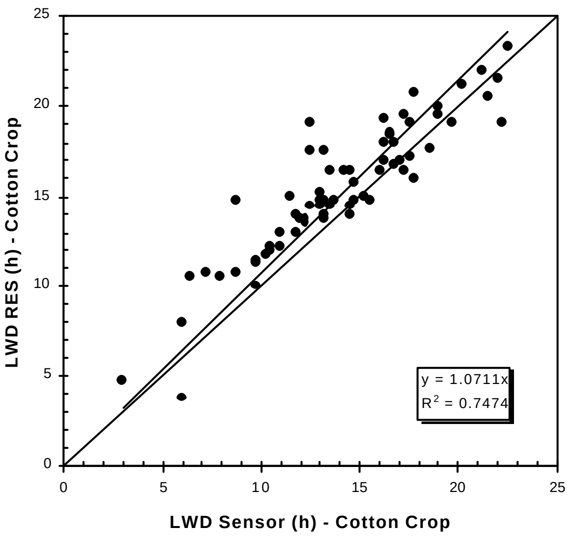

Figure 8. Relationship between LWD estimated by the RES model, using data from the micro-stations inside the cotton crop, and LWD measured by the flat-plate sensors. Each point for LWD obtained with the micro-stations is the average of 3 measurements points in each cultivar.

f) RES model was a good option to estimate LWD at the crop level, having estimates good agreement with measurements in the micro-stations and being capable to reproduce the same relationship between LWD measured in the crop level and in the weather station.

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