SUITABILITY OF RELATIVE HUMIDITY AS AN ESTIMATOR OF LEAF WETNESS DURATION

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ABSTRACT: The objective of this study was to evaluate the performance of three RH-based empirical models to estimate leaf wetness duration (LWD) in four regions around the world that have different climate conditions. Hourly LWD, air temperature, and relative humidity data were obtained from Ames, Iowa state (USA), Elora, province of Ontario (Canada), Florence, Toscany region (Italy), and Piracicaba, São Paulo State (Brazil). These data were used to evaluate the performance of the following empirical LWD estimation models: constant RH threshold (RH≥90%); dew point depression (DPD); and extended RH threshold (EXT_RH). Different performance of the models was observed in the four locations. In Ames, Elora and Piracicaba, the RH≥90% and DPD models underestimated LWD, whereas in Florence these methods overestimated LWD, especially for shorter wet periods. When the EXT_RH model was used, LWD was overestimated for all locations, with a significant increase in the errors. In general, the RH≥90% model performed best, presenting the highest general fraction of correct estimates (FC), between 0.87 and 0.92, and the lowest false alarm ratio (FAR), between 0.02 and 0.31. The use of specific thresholds for each location improved accuracy of the RH model substantially, even when independent data were used, with mean absolute error (MAE) ranging from 1.2 to 1.9 h, which is very similar to errors obtained with published physical models.
KEYWORDS: dew, empirical models, plant disease warning system.

VIABILIDADE DA UMIDADE RELATIVA COMO UM ESTIMADOR DA DURAÇÃO DO PERÍODO DE MOLHAMENTO FOLIAR

RESUMO: O objetivo deste estudo foi avaliar o desempenho de três modelos empíricos de estimativa da duração do período de molhamento foliar (DPM), baseados na umidade relativa do ar, em quatro regiões ao redor do mundo, com diferentes condições climáticas. Dados horários de DPM, temperatura (T) e umidade relativa (UR) do ar foram obtidos em Ames, no estado de Iowa (EUA), em Elora, na província de Ontario (Canadá), em Florença, na região da Toscana (Itália) e em Piracicaba, no estado de São Paulo (Brasil). Esses dados foram usados para avaliar o desempenho dos seguintes modelos empíricos de estimativa da DPM: limiar constante de UR (UR≥90%); depressão do ponto de orvalho (DPO); e limiar estendido de UR (EST_UR). Os modelos apresentaram diferentes desempenhos nas quatro localidades. Em Ames, Elora e Piracicaba, os modelos UR≥90% e DPO subestimaram a DPM, enquanto que em Florença esses modelos superestimaram a DPM, especialmente para os períodos de molhamento mais curtos. Quando o modelo EST-UR foi empregado, a DPM foi superestimada em todas as localidades, com significativo aumento dos erros. Em geral, o modelo UR≥90% foi o de melhor desempenho,

apresentando a maior fração de estimativas corretas (FC), entre 0,87 e 0,92, e a taxa de falso alarme (FAR), entre 0,02 and 0,31. O uso de limiares específicos para cada localidade aumentou substancialmente a acurácia do modelo baseado na UR, mesmo quando dados independentes foram utilizados, com o erro absoluto médio da ordem de 1,2 a 1,9 h, o que é muito similar aos erros obtidos por modelos físicos.
PALAVRAS-CHAVE: orvalho, modelos empíricos, sistema de alerta fitossanitário.

INTRODUCTION: The presence of water on plant surfaces impacts in many biophysical processes, such as the spread of fungal and bacterial diseases, deposition of atmospheric pollutants, leaf gas exchange, and survival of some insects. Concerning crop protection applications, leaf wetness duration (LWD) is a driving variable in epidemiological models for simulating risk of crop damage from many plant diseases (Huber and Gillespie, 1992). Even though the dew condensation process can be easily described from a physical point of view, LWD is a difficult variable to measure since it is the result of interactions among leaf position and arrangement, canopy structure and the atmosphere (Sentelhas et al., 2004, 2006). Many efforts have been made to overcome the problem of LWD measurement. Since the 1980s simulation models have been developed following different approaches. Models can be divided into two broad categories - empirical and physical, based on both agrometeorological and crop criteria. Physical models are based on energy balance principles, requiring inputs that are not always available. In contrast, empirical models can simulate LWD by using simple relationships of this variable with parameters measured at standard agrometeorological stations, mainly relative humidity (RH). As RH can be easily measured at an hourly step, the objectives of this study were: a) evaluate the ability of three simple RH-based empirical models to estimate LWD in four locations around the world, and b) calibrate and test the best of them for each region.

MATERIAL AND METHODS: Leaf wetness duration measurements over turfgrass were done with different sensors, according to the location. Flat plate sensors and electronic transducer sensors were used. All sensors were previously tested and calibrated under laboratory and field conditions. These sensors were connected to dataloggers and programmed to measure the percentage of time in which the sensors were wet during each interval of time, which ranged from 10 to 60 minutes depending on the location. The field experiments were conducted over mowed turfgrass in the following locations where leaf wetness (LWD), temperature (T) and relative humidity (RH) were measured: a) Ames, Iowa, USA (42°01’ N, 93°46’ W); b) Elora, Ontario, Canada (43°49’ N, 80°35’ W); c) Florence, Toscany, Italy (43°45’ N, 11°21’E); d) Piracicaba, São Paulo, Brazil (22°42’ S, 47°30’ W). T and RH data were used to estimate LWD according to the following empirical models: a) Constant RH threshold (RH≥90%) – which considers that wetness is present when RH ≥ 90%; b) Dew point depression (DPD) – where DPD is the difference between air and dew point temperatures – this model considers wetness onset when DPD ≤ 1.8°C and wetness dry-off when DPD ≥ 2.2°C; c) Extended RH threshold (EXT_RH) – this model uses a base RH threshold of 87%, and wetness is extended to lower humidity ranges depending on the rate of change in RH. For periods with RH between 70% and 87%, leaves are assumed to be wet if average RH increases more than 3% in 30 minutes, and leaves are assumed to become dry if average RH decreases more than 2% in 30 minutes. During periods with average RH < 70% leaves are assumed to be dry, and during periods with average RH > 87% leaves are assumed to be wet. To evaluate performance of the empirical models in estimating daily LWD, observed and estimated LWD data were compared by regression analysis and by the Willmott agreement index (D). Also, a confidence index (C) was calculated as the product of the root square of R^2, which expresses the precision of the estimates, and D, which expresses their accuracy. The estimation errors were also determined: mean error (ME) and mean absolute error (MAE). LWD data were also analyzed considering each interval of time in order to quantify the proportion of intervals that were correctly classified as wet or dry, using a contingency table and the following statistical scores: fraction of correct estimates (FC); correct success index (CSI); false alarm ratio (FAR); and bias (BS).

RESULTS AND DISCUSSION: The empirical models performed differently in each location. In Ames, all three models performed unsatisfactorily. There was a systematic LWD underestimation for the RH≥90% and DPD models (Fig. 1a,b). The EXT_RH overestimated by up to 13 h for shorter LWD periods, but underestimated for longer LWD periods (Fig. 1c). In Elora, performance of RH≥90% (Fig. 1d) and DPD (Fig. 1e) models was very similar, mainly underestimates, especially for shorter LWD periods. When EXT_RH was used to estimate LWD at Elora (Fig. 1f), however, the opposite trend was observed; a predominance of overestimates with a higher dispersion of data. In Florence, all three LWD models overestimated LWD, with very similar results for RH≥90% (Fig. 1g) and DPD (Fig. 1h). For EXT_RH model, LWD overestimation was greater and precision of the estimates decreased (Fig. 1i). In Piracicaba the RH≥90% model resulted in relatively accurate LWD estimates with very small underestimates (Fig. 1j). Precision of the estimates increased slightly when the DPD model was used, but the magnitude of underestimation increased (Fig. 1k). As at the other locations, using the EXT_RH method in Piracicaba resulted in LWD overestimation and in an increase of data dispersion (Fig. 1l).

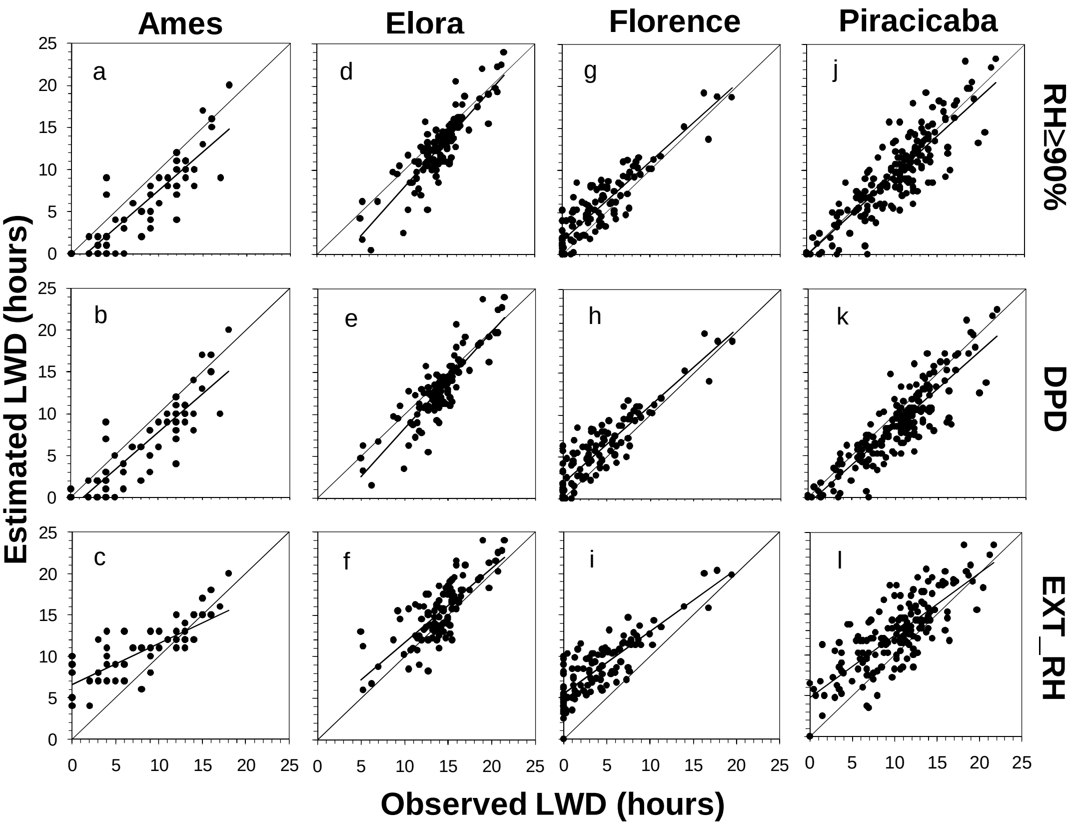

Figure 1 - Relationship between LWD measured and estimated by empirical models in Ames, USA (a, b, c), Elora, Canada (d, e, f), Florence, Italy (g, h, i) and Piracicaba, Brazil (j, k, l*)*.

In general, accuracy differed little between RH≥90% and DPD models. Results of regression analysis were very similar for accuracy and precision of the estimates, with R^2 ranging from 0.75 to 0.82, D ranging from 0.88 to 0.92, C ranging from 0.77 to 0.83, and MAE $\leq$ 2.61 h. The EXT_RH model had the worst performance, with the lowest precision (R^2 from 0.61 to 0.71), accuracy (D from 0.76 to 0.85) and confidence (C from 0.63 to 0.66), and the highest MAE (from 2.3 to 4.4 h).

Analyzing the statistical scores from the contingency table (Table 1), it is possible to evaluate the performance of the models further, since this analysis shows how accurately each model estimated wet and dry periods. By this analysis, RH≥90% and DPD models performed similarly with FC ranging from 0.87 to 0.92, and CSI from 0.66 to 0.87, across the four locations. FC and CSI values decreased to less than 0.89 and 0.83, respectively, for most locations when the EXT_RH model was used. FAR increased substantially, explaining the general LWD overestimation by the EXT_RH model, as shown by the fact that the Bias index was always greater than 1, which is also shown by positive values of ME.

Table 1 - Statistical scores calculated by comparing LWD measured by the sensors and estimated by different models: RH≥90%; DPD; EXT_RH. Legend: F_C = fraction of correct estimates; C_{SI} = correct success index; F_{AR} = false alarm ratio; B_S = bias.

Place	Model	F_C	C_{SI}	F_{AR}	B_S
Ames	RH≥90%	0.87	0.66	0.06	0.74
Elora		0.92	0.86	0.02	0.90
Florence		0.92	0.65	0.31	1.34
Piracicaba		0.90	0.79	0.09	0.93
Ames	DPD	0.88	0.67	0.07	0.76
Elora		0.92	0.87	0.03	0.92
Florence		0.91	0.65	0.32	1.38
Piracicaba		0.87	0.62	0.09	0.85
Ames	EXT_RH	0.83	0.65	0.29	1.26
Elora		0.89	0.83	0.13	1.09
Florence		0.80	0.46	0.54	2.10
Piracicaba		0.85	0.73	0.23	1.22

Because the RH and DPD models performed best at all locations and no significant differences were observed between them, the RH model was selected for calibration, since it is the simplest model. The process of calibration determined the following thresholds: 83% for Ames; 85% for Elora; 92% for Florence; and 90% for Piracicaba. The new RH thresholds were validated with independent data for all sites. Results from this analysis are presented in Table 2. The performance of the RH model with independent data was very similar to that with data used for calibration of the model, with good precision (R^2 ranging from 0.80 to 0.89) and high accuracy (D ranging from 0.92 to 0.97), resulting in a C index ranging from 0.84 to 0.92. The same was observed for MAE, which was always smaller than 1.8 h.

The results presented in this study are a comprehensive analysis of RH-based empirical models to estimate daily LWD in different climates around the world. This fact makes our findings robust and broadly adaptable to many climates. Our purpose in this study was not to asset that RH-based empirical models are better than more complex models to estimate LWD, since the latter ones can produce highly accurate results (Pedro and Gillespie, 1982a,b; Francl and Panigrahi, 1997; Sentelhas et al., 2006), but to show how useful these simple models can be to estimate LWD when only RH data are available.

Table 2 - Regression analysis, statistical indices and errors for the comparison between LWD measured by sensors and estimated by RH model when calibrated locally (data independent from the calibration process) for Ames (USA); Elora and Ridgetwon (Canada); Florence (Italy); and Piracicaba (Brazil).

Place	a	b (h)	R^2	D	C	ME (h)	MAE (h)
Ames	1.06	0.17	0.85	0.95	0.88	0.75	1.78
Elora-Ridgetwon	0.96	0.04	0.80	0.94	0.84	-0.53	1.60
Florence	0.75	2.95	0.87	0.92	0.86	0.92	1.71
Piracicaba	0.95	0.28	0.89	0.97	0.92	-0.25	1.29
General	0.92	1.20	0.86	0.96	0.89	0.36	1.63

CONCLUSIONS: RH-based empirical models for LWD estimation, when not calibrated locally, performed differently at four locations with contrasting climate. Both RH≥90% and DPD models consistently underestimated LWD in Ames, Elora and Piracicaba, and overestimated it in Florence. The EXT_RH model was least able to estimate LWD, resulting in much lower precision and accuracy than the RH and DPD models. When the RH model was locally calibrated, the accuracy of LWD estimates improved substantially, and resulting errors were small enough (< 2h) to provide inputs for plant disease-warning systems.

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