Suitability Evaluation of Four Methods to Estimate Leaf Wetness Duration in a Greenhouse Rose Crop

R. Gil[a] and C.R. Bojacá[b]
Centro de Investigaciones y Asesorías
Agroindustriales
Universidad de Bogotá
Jorge Tadeo Lozano
PO Box 140.196 Chía
Colombia

E. Schrevens[c]
Department of Biosystems
Faculty of Applied Bioscience Engineering
Katholieke Universiteit Leuven
Geo-institute
Celestijnenlaan 200-E, Leuven
Belgium

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Abstract

A water-film above the leaf surface is a necessary condition for the start of the infective process of many pathogens. Therefore, the Leaf Wetness Duration (*LWD*) has a strong relationship with the development and outbreak of plant diseases. The occurrence of free water on leaf surfaces is a common situation for the simple plastic greenhouses used to grow ornamental crops in the Bogota Plateau (Colombia). The objective of this work was to evaluate the suitability of four models to predict *LWD* occurrence in a greenhouse rose crop. Model performances were compared against the measurement of dielectric leaf wetness sensors, placed at 1.2 and 1.8 m above the ground, within two sampling locations inside a greenhouse during a 25-day period. Sensors were connected to dataloggers, programmed to store data every 10 min. Two copper-constantan thermocouples measured air and wet-bulb temperature and were used to calculate relative humidity (*RH*). Three empirical models were evaluated: Constant *RH* threshold (*RH*≥90%), locally calibrated *RH* threshold (*RH*≥94%) and dew point depression (*DPD*). Also, one physical model that estimates *LWD* based on the latent heat flux (*LE*) of the leaf was considered. As a result the following four scores were calculated: fraction of correct estimates, correct success index, false alarm ratio and bias. *LWD* estimated at 1.8 m above the ground showed the best performance for all the empirical models whereas the physical model yielded the best results for measurements made at 1.2 m. The results obtained with the models indicated a differential degree of success for the prediction of *LWD*. In general, *RH* and *DPD* with thresholds of 94% and 2°C respectively were the most suitable models to estimate *LWD*, resulting in higher precision and accuracy. The results will contribute to the development of integrated pathogen management in greenhouse rose crops in the Bogota Plateau.

INTRODUCTION

In Colombia, the area cultivated with fresh cut flowers is around 7266 ha, which makes it the second largest exporter of flowers in the world after The Netherlands. Cultivation of fresh cut-roses (*Rosa* spp.) in greenhouses in the Bogota plateau represents 30% of the total area cultivated with flowers in Colombia (Asocolflores, 2008). Among the sanitary problems, downy mildew (*Peronospora sparsa*) is a very serious disease for the local crops. Downy mildew is mainly chemically controlled with regular applications based on monitoring schemes. The pathogen development is driven by the bio-environmental conditions, in particular, leaf wetness duration (*LWD*). A water-film on the leaf surface is a necessary condition for the start of the infective process of many pathogens (Rosa et al., 1995; Orlandini and Rosa, 1997; Rosa and Orlandini, 1997; Sentelhas et al., 2008).

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[a] rodrigo.gil@utadeo.edu.co
[b] carlos.bojaca@utadeo.edu.co
[c] eddie.schrevens@biw.kuleuven.be

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In greenhouses, leaf wetness is caused by condensation. This event occurs when the leaf surface is colder than the dew point temperature of the surrounding air (Sentelhas et al., 2008). Such process is due to the radiative loss of heat from the leaf to the air, a situation that is commonly achieved during cool nights. Many simulation models have been developed to determine or to predict *LWD*; these models can be categorized as: empirical or physical, with both relying on agrometeorological and crop variables. Physical models are based on energy balance principles. Pedro and Gillespie (1982) proposed the use of the latent heat flux (*LE*) to infer *LWD*. On the other hand, empirical models rely on fitted functions built upon meteorological data (Sentelhas et al., 2008).

LWD has a strong relationship with the development and outbreak of downy mildew in rose crop under greenhouse conditions. However, for greenhouses located in the tropics dedicated to rose cropping, there is no information about the performance of the available models to estimate *LWD*. Therefore, the objective of this work was to evaluate the suitability of four models to predict *LWD* in a rose crop under protected conditions. Modelling and accurate simulation of *LWD* will be the corner stone for a downy mildew warning system.

MATERIALS AND METHODS

A rose crop, grown in a multispan plastic greenhouse in the Bogota Plateau (4°50’41”N; 74°10’09”W at an altitude of 2591 m), with a total area of 5410 m^2 was used to measure the *LWD*. Dielectric leaf wetness sensors (*LWS*-L, Decagon Devices Inc.) were calibrated under laboratory conditions. For model construction, the following measurements were performed: leaf temperature (T_L) using infrared radiometers (IR, model SI-111, Apogee Instruments Inc.); air temperature (T_A) and relativity humidity (*RH*), by means of copper-constantan thermocouples coupled to remote dataloggers (Cox-Tracer Junior, Escort DLS Inc.). The *RH* was calculated from T_A and wet-bulb temperatures using a psychrometric chart. Thermocouples were placed within white plastic reflective boxes. These boxes were artificially ventilated by a small fan (wind speed between 1 to 3 m s^{-1}). *LWS*-L and T_L sensors were connected to dataloggers (CR1000, Campbell Scientific) and programmed with a 10-min time interval. Four individual sensors (*LWS*-L and radiometers) and four pairs of thermocouples (wet and dry bulb), were installed in two sites and two heights (1.2 and 1.8 m above ground) per site inside the greenhouse during a 25-day measurement period. The threshold logger reading for *LWS*-L was determined in a laboratory; values smaller or equal to 271 mV indicated a wet condition (1), whereas greater values indicated a dry situation (0). Each *LWS* was mounted on metal tubing, with an inclination angle of 45°, together with the T_L, T_A and *RH* sensors. Outside global solar radiation and wind speed were recorded with the use of an automated weather station.

LWD Models

Three empirical models were evaluated. The first model, named *RH≥90%*, was proposed by Sentelhas et al. (2008) and assumes that *LWD* is equal to the number of hours where *RH* is equal or greater to a constant threshold of 90%. The second was (*RH≥94%*) a modification of the previous model, where the *RH* threshold was calibrated according to the local conditions and set to 94%. The third one was the dew point depression (*DPD*), this model uses the difference between T_A and dew point temperature (T_D) to determine *LWD*. Although the DPD model was proposed by Sentelhas et al. (2008) the wetness threshold was adapted for the local conditions. This local threshold was determined by comparing the presence or absence of wetness predicted by the DPD model evaluating a range of thresholds (*RH* from 85 to 98% and *DPD* from 1.2 to 2.2°C) against the one observed with the *LWS*-L sensors. For the present work, the threshold for the starting of a wetness period was when *RH*≥94% and *DPD*<2°C.

The physical model is based on the work of Pedro and Gillespie (1982); it uses the latent heat flux (*LE*) of the leaf to infer the *LWD*. The model is defined by the following equations:

$$LE = -\left(\frac{0.622}{P}\right)2hw(e_{sl} - e) \tag{1}$$

where

$$hw = 1.07\frac{L_V}{C_p}hc \tag{2}$$

and

$$hc = \frac{Nu\lambda}{D} \tag{3}$$

where; P is the atmospheric pressure (mb), hw (W·m^{-2}) is the water vapor transfer coefficient, e_{sl} is the saturated vapor pressure (mb) at T_L, e is the ambient vapor pressure (mb), hc is the heat transfer coefficient (W·m^{-2} °C^{-1}), L_V is the latent heat of vaporization of water (J kg^{-1}), C_P is the specific heat of the air (J kg^{-1} °C^{-1}), Nu is the Nusselt number, λ is the thermal conductivity of still air (W m^{-1} °C^{-1}) and D is the effective leaf diameter (m). Duration of the dew period was inferred as follows: onset occurs when $LE>0$ and ends when the condensation accumulated during the night is consumed by an equivalent amount of evaporation during the morning (Pedro and Gillespie, 1982).

Data Analysis

In order to evaluate the performance of the empirical and physical models, contingency tables (Wilks, 1995) were used to determine the proportion of events correctly classified as wet or dry. Through the sum of events in each category for a given model fraction of corrects estimates (F_C), correct success index (C_{SI}), false alarm ratio (F_{AR}) and bias (B_S) were calculated as follows

$$F_C = \frac{A+D}{A+B+C+D} \tag{4}$$

$$C_{SI} = \frac{A}{A+B+C} \tag{5}$$

$$F_{AR} = \frac{C}{A+C} \tag{6}$$

$$B_S = \frac{A+C}{A+B} \tag{7}$$

where, A was a hit (observed wet event and correctly detected by the model), B represented a miss (observed wet event but not detected by the model), C was a false alarm (wet not observed but detected by the model) and D was a correct negative (wet not observed and not detected by the model).

The three first scores vary from 0 to 1, the best model must have F_C and C_{SI} values close to 1, while F_{AR} values must be near 0. Finally, B_S values lower than 1 indicates underestimation while values above 1 indicate overestimation. In order to determine the possible differences between models, an analysis of variance (α=0.05) was done. Additionally, wet profiles for each sensor were integrated over 24-h periods (from 12:00 pm to 11:59 am of the next day). Thus, observed versus estimated LWD data were compared by regression analysis and mean absolute error (MEA) was calculated. Finally, in order to evaluate models suitability the criteria suggested by Magarey et al. (2006) were discussed.

RESULTS AND DISCUSSION

The measures of T_L and T_A were not affected by the height of the sensors. Figure 1a shows hourly averages of T_L measured at 1.2 and 1.8 m above the ground and it can be seen that during most of the day T_L was similar at the two heights. The daily mean of T_L at 1.2 and 1.8 m were of 13.71 and 14.15°C respectively. The hourly average of T_A, measured at the two same heights, presented nearly similar values (Fig. 1b) with daily average values of 13.86 and 13.92°C at 1.2 and 1.8 m in that. During the 24-h period, the T_L at 1.8 m (Fig. 1a) was slightly higher than the T_L at 1.2 m. The higher degree of exposition of the upper leaves to direct radiation during day hours is responsible for such differences, especially around noon. In contrast, the T_A at 1.8 m during night hours was lower than at 1.2 m due to the heat flux that arises from the soil. The number of hours per day that sensors at 1.8 m remained wet was 12.9 h while at 1.2 m a shorter period was observed (10.5 h). The results of this work indicate the presence of a vertical gradient for leaf wetness duration. Kim et al. (2008) reported *RH* variability along the vertical profile inside a greenhouse. These authors found accumulations of moisture at heights greater that 1.5 m, which partly coincides with the *LWD* results obtained for the upper height evaluated in this work. Figure 2a and b show clearly that leaf wetness occurrence and duration is in direct relationship with high *RH* and low *DPD* values.

Models Evaluation

The results obtained with the models indicated a differential degree of success for the prediction of *LWD*. The scores for each model at a given height, presented in Table 1, indicate significant differences ($P<0.05$) according to the results of the analysis of variance for F_C ($F=5.68$; df=3), C_{SI} ($F=5.09$; df=3), F_{AR} ($F=204.37$; df=3) and B_S ($F=8.39$; df=3). In general, the three empirical models based on *RH* and *DPD* showed the best event (i.e., dry or wet) prediction. However, *RH≥90%* and *RH≥94%* models showed a slightly better performance to estimate *LWD* as can be inferred from all the scores considered. For *RH≥90%* and *RH≥94%* models, F_C and C_{SI} values were the higher at both measurement heights, while F_{AR} showed the lowest value. The B_S score indicated that all models, exception made for *LE* at 1.8 m, tended to overestimate *LWD*. The scores for the *LE* model showed a poor performance to estimate *LWD* and only scores obtained at 1.2 m exhibited values close to those of the empirical models.

Although, the scores of *RH*-based models were in the same range, regression analysis indicated the best fit for *DPD* followed by *RH≥94%* at 1.8 m while at 1.2 m *LE* was followed by *RH≥90%* (Fig. 3). For the position inside the canopy, contingency table and regression analysis indicated the best performance for the empirical models at 1.8 m, while the physical model only presented an acceptable performance at 1.2 m. These differences could be a result of the degree of exposition of the sensors to sunlight. Sensors placed at 1.8 m were almost fully exposed to incoming radiation on top of the canopy and dried faster than sensors at 1.2 m.

The final factor analyzed to choose an appropriate model was the *MAE* of each model at the two heights. Sentelhas et al. (2008) suggest that an *LWD* model with *MAE* lower than 2 h can be used as one of the tools for warning systems in plant disease management schemes in places where basic weather data sets are available. The presence of leaf wetness is essential for disease starting an infection and *LWD* is a fundamental agrometeorological variable to construct a predictive model as proposed by Rosa et al. (1995) and Orlandini and Rosa (1997). *RH≥94%* and *DPD* models at 1.8 m presented the lowest *MAE* with 0.84 and 0.72 h, respectively. *RH≥90%* and *LE* showed *MAE* values of 1.11 and 4.53 h, respectively. At this height (1.8 m) the upper third of the plant can be found and it is the zone where the greatest proportions of young leaves are present. In turn, these types of leaves are the ones more susceptible to *P. sparsa* infections (Gómez, 2004). In contrast, all models evaluated at 1.2 m presented MAE values higher or equal to 1.97 h.

Margarey et al. (2006) suggested six criteria to evaluate the suitability of a particular *LWD* model. For the present work, these are used to discuss the suitability of the best qualified models in previous stages. However, evaluation criteria such as scalability and calibration under controlled conditions are not discussed because of the absence of the necessary data in the present work. The first criterion was the simplicity, the *RH≥94%* model only request *RH* as an input, while *DPD* despite of being an empirical model requests additional calculation. However, a disadvantage of both models is that they need to be calibrated due to changes in conditions such as e.g., change of measuring equipment or geographical location. Most rose growers have *RH* sensors at least in one of their greenhouses and *RH*-based models can be easily implemented. In contrast, physical models require variables that are not easy to measure or readily available. Model adoption could be retarded when a complex model is chosen (Magarey et al., 2006). The second criterion is the utility. A model is considered useful if it includes all the events that can cause the occurrence of leaf wetness. The *RH≥94%* model fulfills the second criterion, under greenhouse conditions the main factor that causes leaf wetness is condensation and, as it is shown in Figure 2a, *RH* can characterize *LWD*. The third criterion is the type of unit of the simulation result; a good model must have units easily measured in the field. For a validation of any *LWD* model it is convenient to compare simulated output against measured values in terms of the same units. In the case of the *LE* model (Pedro and Gillespie, 1982), it uses latent energy units as the output (W m^{-2}), which may require specialized equipment for field verification. In contrast, the *RH≥94%* model is able to estimate the wetness in the same unit as *LWS*: wetness or dry. The fourth criterion is the capacity of a particular model to be adapted to new sites and crops. According to the results *RH* and *DPD* models could be adapted for the greenhouse ornamental production areas of Colombia. However, as previously explained, the *RH≥94%* model had the best performance and its adoption potential may be considered higher. The physical model (*LE*) requires more information about the plant such as height, leaf area index and water storage per unit of area.

Knowledge of a wide range of atmospheric conditions and diverse plant characteristics is necessary to estimate *LWD* using the physical model (*LE*), while the simplicity, utility, type of units and adaptability easiness of empirical models allows a quick validation and transfer to growers. For the empirical models evaluated, the results presented in this study allow to conclude that the *RH≥94%* model is the more suitable to estimate leaf wetness duration for a rose crop growing under protected conditions in Bogota. The location of the *RH* sensors in the canopy will vary depending on the development stage of the plant. Over the growing cycle, *RH* sensors must always be located at the height where young leaves are present.

CONCLUSIONS

Empirical models based on relative humidity to estimate leaf wetness duration demonstrated to be reliable enough to be included as part of a disease warning model for a greenhouse rose crop. Simplicity, easiness for adoption and equipment required made such models adequate for a commercial application that can be used by all growers.

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Tables

Table 1. Scores calculated by comparing *LWD* observed events against estimated events within a greenhouse rose crop by four models: constant *RH* threshold (*RH*≥90%), calibrated *RH* threshold (*RH*≥94%), dew point depression (*DPD*), and latent heat flux (*LE*).

Model	1.8 m				1.2 m			
	F_C	C_{SI}	F_{AR}	B_S	F_C	C_{SI}	F_{AR}	B_S
RH≥90%	0.90	0.82	0.14	1.10	0.81	0.69	0.29	1.37
RH≥94%	0.90	0.83	0.14	1.10	0.81	0.69	0.29	1.37
DPD	0.86	0.77	0.21	1.22	0.77	0.65	0.34	1.49
LE	0.63	0.28	0.15	0.40	0.81	0.69	0.29	1.37

Figures

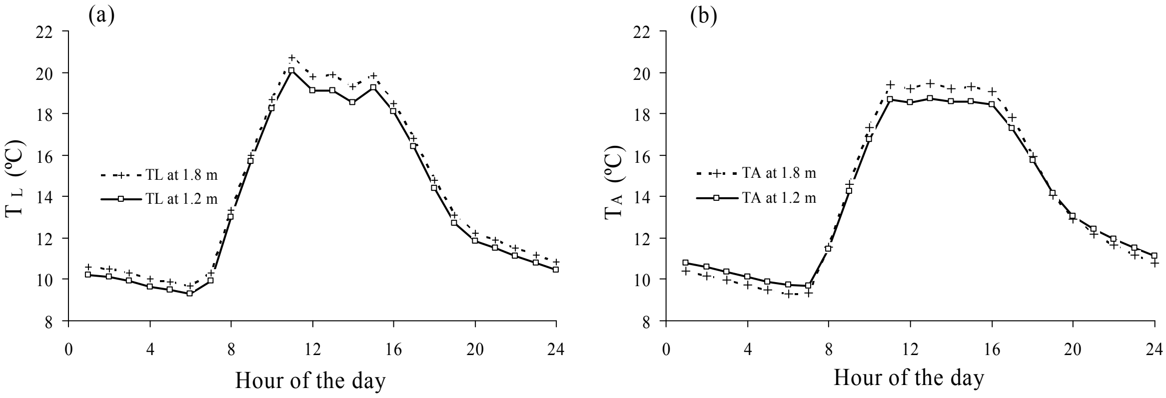

Fig. 1. Daily variation of (a) leaves and (b) air temperatures measured at two heights within the canopy of a greenhouse rose crop.

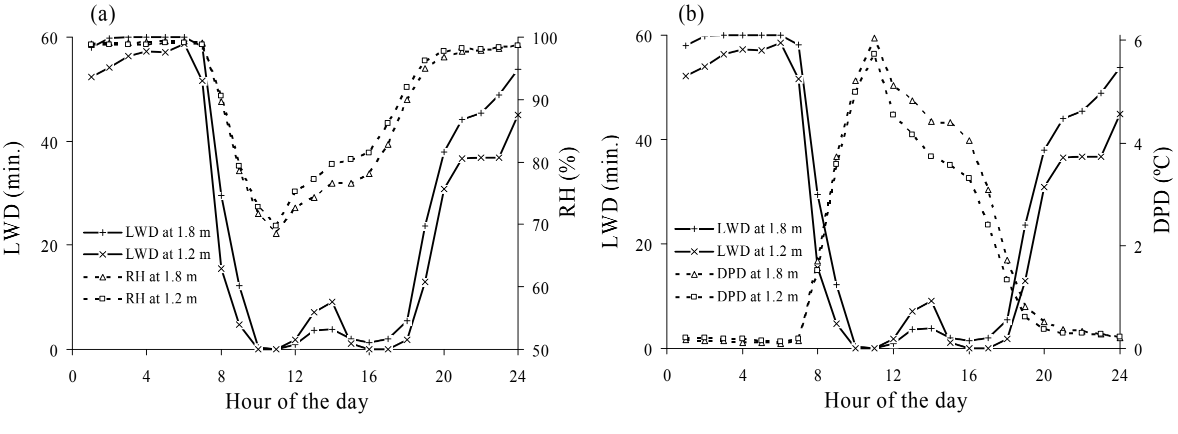

Fig. 2. Hourly averages of observed leaf wetness duration (*LWD*), (a) relative humidity (*RH*) and (b) dew point depression (*DPD*) measured at two heights within the canopy of a greenhouse rose crop.

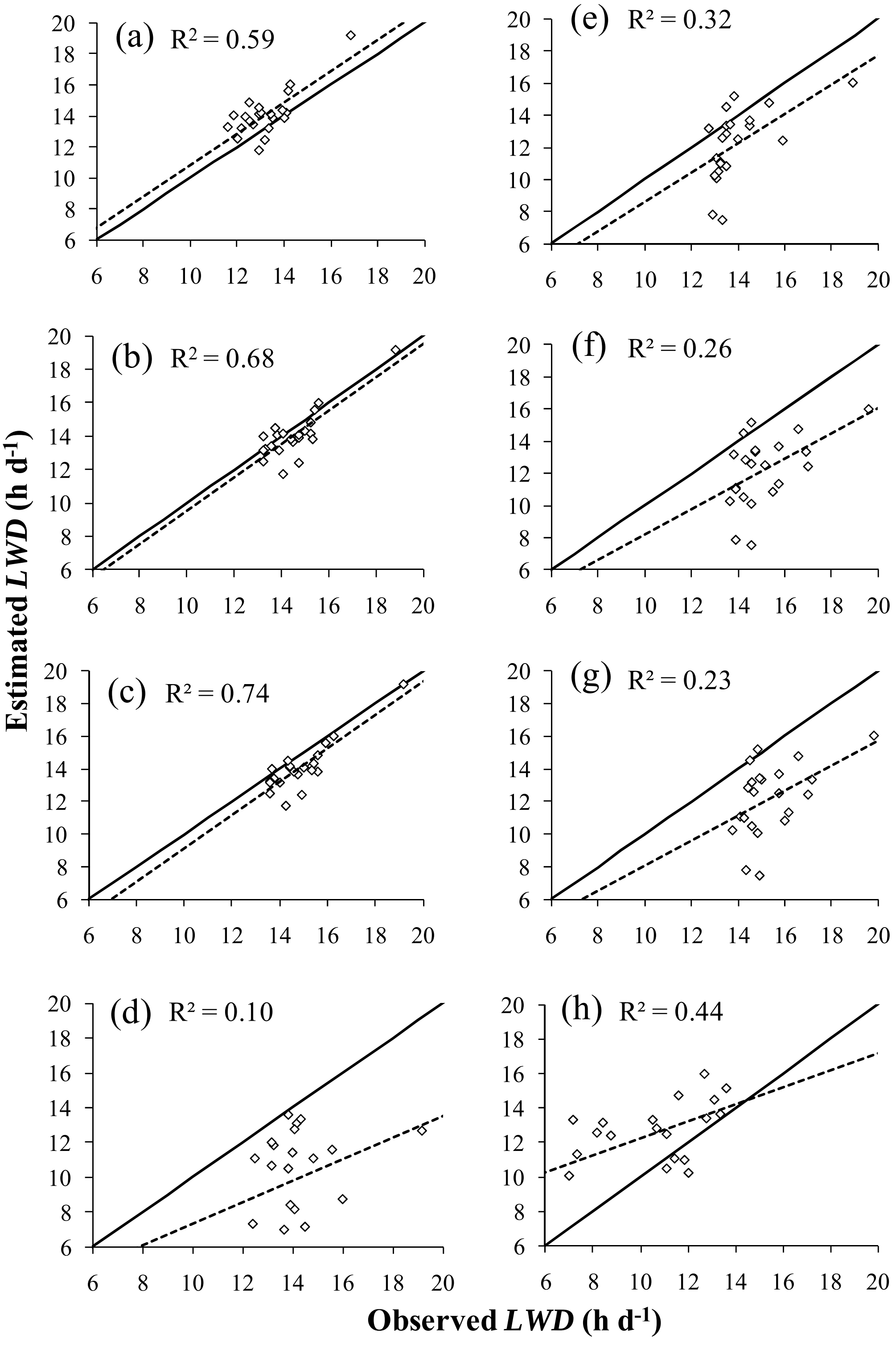

Fig. 3. Regression analysis between observed and estimated *LWD* integrated over 24-h periods. Continuous line represent a 1:1 relationship and segmented line is the regression line of observed versus estimated values. (a) *RH≥90%* model at 1.8 m; (b) *RH≥94%* model at 1.8 m; (c) *DPD* at model 1.8 m; (d) *LE* model at 1.8 m; (e) *RH≥90%* model at 1.2 m; (f) *RH≥94%* model at 1.2 m; (g) *DPD* model at 1.2 m; (h) *LE* model at 1.2 m.