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Agricultural and Forest Meteorology 141 (2006) 105–117

AGRICULTURAL AND FOREST METEOROLOGY

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Evaluation of a Penman–Monteith approach to provide "reference" and crop canopy leaf wetness duration estimates

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Received 27 March 2006; received in revised form 25 July 2006; accepted 15 September 2006

Abstract

Leaf wetness duration (LWD) is a key parameter for plant disease-warning systems since the risk of outbreaks of many plant diseases is directly proportional to this environmental variable. However, LWD is not widely measured so several methods have been developed to estimate it from weather data. Methods based on the physical principles of dew deposition and dew or rain evaporation have shown good portability and sufficiently accurate results for operational use. A Penman–Monteith approach to modeling LWD on a "reference" wetness sensor located at a weather station was investigated as well as the use of an empirical wetness coefficient (*W*) to convert "reference" LWD into crop LWD. This study was undertaken because recent observations revealed that an LWD sensor located about 30 cm above a turfgrass surface provided useful estimates of LWD in various nearby crops, suggesting that modeling such a sensor and location may be a simpler "reference" alternative to modeling LWD in a crop canopy. LWD was measured over mowed turfgrass at different heights (30, 110, and 190 cm above the ground) and at the top of the canopy of eight crops – apple, coffee, cotton, maize, muskmelon, grape, soybean, and tomato – using painted flat-plate sensors. At the same times and places, automatic weather stations measured air temperature, relative humidity, wind speed, and net radiation over turfgrass. A Penman–Monteith approach estimated sensor LWD over turfgrass with very good accuracy and precision, using an additional aerodynamic resistance based on wind speed to estimate LWD at 110 and 30 cm. The model overestimated LWD by 3.3% at 190 cm ($R^2 = 0.92$), 1.5% at 110 cm ($R^2 = 0.87$), and 5.7% at 30 cm ($R^2 = 0.89$). When modeled LWD for a 30-cm height over turfgrass was correlated with LWD measured at the top of crop canopies, strong agreement was observed, with an average overestimation of 6.3% and a coefficient of determination of 0.92 for five crops combined. The use of both general and specific *W* coefficients reduced the average overestimation and the mean absolute error in LWD to less than 1 h/day. When independent data from four crops were use to evaluate crop LWD estimates by this two-step Penman–Monteith approach, mean absolute error was <1.6 h when both general and specific *W* coefficients were used. We concluded that a Penman–Monteith model for a fixed sensor size, albedo and exposure over turfgrass may be a very useful "reference" index to estimate crop LWD for use in plant disease management schemes.

Keywords: Dew; Rain; Physical model; Plant disease; Warning system; Integrated pest management

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0168-1923/$ – see front matter
doi:10.1016/j.agrformet.2006.09.010

1. Introduction

Leaf wetness is recognized as a very important weather parameter for plant disease epidemiology (Pedro, 1980; Huber and Gillespie, 1992; Gleason et al., 1994; Kim et al., 2002). The time that free water remains on the surface of plant tissues, termed leaf wetness duration (LWD), is fundamental for bacterial and fungal disease development, so the risk of outbreaks of many crop diseases is directly proportional to this environmental variable (Huber and Gillespie, 1992). For this reason, LWD, together with air temperature, has been used successfully in many weather-based plant-disease management schemes like Downcast for onions (Jesperson and Sutton, 1987), Tomcast for tomatoes (Pitblado, 1992), Melcast for muskmelons (Latin and Egel, 2001), and others.

Because LWD is not widely measured, several methods have been developed to estimate it from weather data (Pedro and Gillespie, 1982a,b; Huber and Gillespie, 1992; Gleason et al., 1994; Rao et al., 1998; Sentelhas et al., 2004a; Magarey et al., 2005). Methods based on the physical principles of dew deposition and the evaporation of dew or intercepted rain have shown good portability and sufficiently accurate results for operational use. Examples of application of physical models of LWD include maize, soybean, and apple (Pedro and Gillespie, 1982a,b), onion (Gillespie and Barr, 1984), sunflower (Garín et al., 1997), banana plantation (Lhomme and Jimenez, 1992), apple (Wittich, 1995), maize ears (Rao et al., 1998), grapes (Magarey, 1999, and Dalla Marta et al., 2005), rice (Lou and Goudriaan, 1999, 2000), and canola (Papastamati et al., 2004). However, these models require net radiation (R_n) as input, which is seldom measured directly over crops or even in a standard weather station (Madeira et al., 2002). When direct measurements of R_n are not available, R_n estimates can be based on combinations of incoming solar radiation, air temperature, relative humidity, cloud cover, and cloud height (Pedro, 1980; Jegede, 1997; Iziomon et al., 2000; Madeira et al., 2002).

Among the physical models used to estimate wetness deposition and evaporation, the one based on the Penman–Monteith equation (Monteith and Unsworth, 1990) has some advantages in relation to those based on an energy balance approach (Pedro and Gillespie, 1982a,b). The main advantage is elimination of the requirement for an air temperature measurement at crop (leaf) level. The Penman–Monteith approach assumes that air temperature measured at a given height above turfgrass at a standard weather station is equivalent to temperature at the same height above the top of a crop canopy, and that adding a resistance item to the model is enough to account for the air layer from measurement height, above the canopy, to the level of the leaves (Rao et al., 1998). Results of Lou and Goudriaan (1999, 2000) in a tropical region of Phillipines, Jacobs et al. (2002) in an arid Mediterranean region, Rao et al. (1998) in southern Canada, and Sentelhas et al. (2004a) in a tropical region of Brazil, have shown that Penman–Monteith approaches estimated LWD very well under diverse climatic conditions.

According to Zhang and Gillespie (1990), estimation of crop LWD with weather data taken outside a crop field could be a two-step process where a ‘‘correction’’ is first applied to the station data before using it in a crop model. Considering this idea, and the recent results presented by Sentelhas et al. (2004b, 2005) which showed that LWD measurements at 30 cm over turfgrass were very similar to those obtained near the top of five different crop canopies of different height and architecture (apple, coffee, maize, grape, and muskmelon), it was hypothesized that a ‘‘reference’’ LWD, estimated by a Penman–Monteith approach using weather data, could provide an accurate estimate of crop LWD when multiplied by a wetness coefficient, similar to the process used to estimate crop evapotranspiration (Allen et al., 1998). To test our hypothesis the following goals were set:

(a) Evaluate a Penman–Monteith approach to modeling LWD on a wetness sensor located in a standard weather station to provide a simple ‘‘reference’’ LWD.
(b) Compare estimated ‘‘reference’’ LWD with measured crop LWD obtained in five different nearby crop canopies: coffee, grape, maize, soybean, and tomato.
(c) Assess the ability of an empirical wetness coefficient (W) to convert ‘‘reference’’ LWD into crop LWD.

2. Material and methods

2.1. Leaf wetness duration measurements

Leaf wetness duration measurements over turfgrass and at the top of the crop canopies were done with flat plate sensors (Model 237, Campbell Scientific, Logan, UT) connected to dataloggers (Models 21X and CR23X, Campbell Scientific, Logan, UT) programmed to measure the percentage of time in which the sensors were wet during each 15-min interval. Each sensor used in this 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 was determined in a laboratory (Sentelhas et al., 2004b), and values smaller than or equal to this threshold (generally about 9000 kΩ) were considered wet while greater values were considered dry. Each LWD sensor was mounted on a section of PVC or metal tubing, with an inclination angle of 30° or 45° and installed in the field.

Flat plate sensors were chosen because of their good performance under different field conditions. Results of Pedro (1980) for apple, soybean, and maize, Lau et al. (2000) for tomatoes, and Sentelhas et al. (2004b) for turfgrass and maize, showed that the differences between sensor measurements and visual observations of wetness were around 15–30 min, confirming the accuracy of flat plate sensors for measuring LWD in different crops.

2.2. Field experiments

The field experiments were conducted on turfgrass and eight crops at four different locations (Table 1), as will be described below. The experiments were not intended to compare between locations, therefore the crops were not replicated over location; but the same general methods were used at all sites.

At Elora, Ontario, Canada (43°49′N, 80°35′W), the LWD sensors were installed over mowed turfgrass (~1 ha plot) at 30-, 110-, and 190-cm-heights and at the top of the canopy in maize, soybean, and tomato fields, about 100–200 m from the sensors on the turfgrass field. LWD sensors were deployed facing north at an inclination angle of 30°. The field experiments were conducted on 71 days from 28 July to 7 October, 2003, when data were collected for turfgrass and maize, and on 35 days from 24 July to 24 September, 2004, when data were collected for turfgrass, soybean, and tomato. In the crop fields, LWD sensors were installed among the leaves in the top one-quarter of the canopy, and their heights were adjusted every week to follow the plant growth.

At Piracicaba, São Paulo State, 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 the top of the canopy (≈80 cm) of a young coffee plantation (~3 ha, northwest–southeast row orientation, cv. Obatã). The measurements were taken from 11 October to 22 December, 2003, totaling 58 days of observations. LWD data were also obtained in a cotton field over 23 days from 01 December, 2005 to 31 January, 2006. In the cotton trial, LWD was measured only at the top of the crop canopy, and sensor height was adjusted every week to follow plant growth.

At Jundiaí, São Paulo State, Brazil (23°06′S, 46°55′W), LWD sensors facing south at an inclination angle of 30° were installed at 30 cm over mowed turfgrass, and at the top (≈160 cm) of a table-grape crop (~0.2 ha, north–south row orientation, cv. Niagara rosada). The measurements were made during 68 days from 24 October, 2003 to 14 January, 2004. The same protocol was used to obtain another LWD data set at the top of the table-grape crop for 54 days from 11 November, 2005 to 16 January, 2006.

At Ames, Iowa State, 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 with the same orientation in two different crops. One sensor was located just below the top (~20 cm above ground) of a muskmelon (cv. Athena) canopy (~0.1 ha) for 30 days from 23 July to 7 October, 2003. Sensors were also deployed in three mature, semi-dwarf (cv. Golden Delicious) apple trees

Table 1
Average climatic conditions during the experiments in Ames, Iowa, USA, Elora, Ontario, Canada, and Jundiaí and Piracicaba, São Paulo State, Brazil

Location	Period (day/month)	Year	Crop(s)	T (°C)	RH (%)	R (mm)	$u_{2\ \mathrm{m}}$ (m s^{-1})
Ames	21 July–30 August	2000	Apple	22.2	82.5	60	2.8
Ames	30 May–28 August	2001	Apple	22.4	74.9	165	3.2
Ames	23 July–07 October	2003	Turfgrass, muskmelon	20.5	75.1	197	3.0
Elora	28 July–07 October	2003	Turfgrass, maize	16.0	83.1	344	1.8
Elora	24 July–24 September	2004	Turfgrass, soybean, tomato	17.8	80.3	133	0.8
Jundiaí	24 October–14 January	2003/2004	Turfgrass, grape	21.8	78.2	478	1.4
Jundiaí	11 November–16 January	2005/2006	Grape	22.0	73.9	523	1.3
Piracicaba	11 October–27 December	2003	Turfgrass, coffee	18.6	65.7	45	1.4
Piracicaba	01 December–31 January	2005/2006	Cotton	23.0	86.1	284	1.4

from 21 July to 30 August, 2000, and in four apple trees from 30 May to 28 August, 2001, totaling 91 days of measurements. Four sensors per tree were placed near the canopy top (3.3 m above the ground) in this orchard (~0.8 ha, north–south row orientation) about 30 cm apart at the same height on an east-west line.

Crop LWD was measured at the top of the eight canopies because that is the position where LWD was greatest in the majority of crops assessed by Sentelhas et al. (2005).

In each location a nearby standard automatic weather station, installed over turfgrass, measured the following variables at 1.9 m above the ground: air temperature (T), relative humidity (RH), wind speed (u), and net radiation (R_n). In Ames, Iowa, however, R_n was not measured. In this case, incoming solar radiation and air temperature data were used to estimate R_n using the model proposed by Iziomon et al. (2000).

2.3. A Penman–Monteith approach to estimate "reference" leaf wetness duration

The Penman–Monteith (P–M) model, also termed the aerodynamic resistance model (RES) by Rao et al. (1998), was applied to estimate latent heat flux (LE), which was used to determine the period of wetness on a "reference" sensor over turfgrass. The main advantage of a P–M model in relation to other physical models to estimate dew amount and duration is that it does not require air temperature measurements at crop (leaf) level. Instead, it assumes that the air temperature measured at a given height above the turfgrass at a standard weather station is representative of the conditions at the same height above the crop canopy, and that an additional resistance in the model accounts for the air layer from the height of the weather-station sensors to the level of the top leaves in the canopy (Rao et al., 1998). This additional resistance is the aerodynamic resistance (r_a, s m^{-1}), as shown in Fig. 1 for wetness sensor above turfgrass surface, which has previously been used for evapotranspiration estimates (Monteith and Unsworth, 1990).

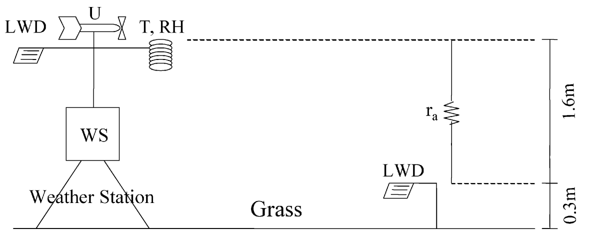

Fig. 1. Schematic of sensor positions and heights over turfgrass and the additional resistance (r_a) required by a Penman–Monteith model to estimate LE.

Using the above concepts, the latent heat flux (LE) for a mock leaf can be estimated for each interval of time using the Penman–Monteith approach (Monteith and Unsworth, 1990):

$$\mathrm{LE} = -\frac{\{sR_n + [1200(e_s - e_a)/(r_a + r_b)]\}}{s + \gamma^*} \quad (1)$$

where s is the slope of the saturation vapor pressure curve (h Pa °C^{-1}), e_s the saturated vapor pressure at the weather station air temperature (h Pa), e_a the actual air vapor pressure (h Pa), γ^* the modified psychrometer constant (assumed to be 0.64 kPa K^{-1} with moisture and heat transfer to both sides of sensor during dew, and 1.28 kPa K^{-1} for evaporation from one side of a sensor after rain), and r_b is the boundary layer resistance for heat transfer (s m^{-1}), given by Monteith and Unsworth (1990):

$$r_b = \frac{D}{\kappa Nu} \quad (2)$$

where D is the effective dimension of the mock leaf (LWD flat plate sensor), equal to 0.07 m, κ thermal diffusivity of air (m^2 s^{-1}), and Nu is Nusselt number, given by:

$$Nu = 0.68Pr^{1/3}Re^{1/2} \quad \text{for} \quad Re < 20{,}000 \quad (3)$$

where Pr = Prandtl number (=0.7019) and Re = Reynolds number:

$$Re = \frac{uD}{\nu} \quad (4)$$

where u = the wind speed (m s^{-1}), obtained from the wind speed profile, and ν = kinematic viscosity of air (m^2 s^{-1}). Substituting Eqs. (3) and (4) in Eq. (2) and rearranging terms r_b (s m^{-1}) results in:

$$r_b = \frac{\nu^{1/2}}{\kappa\, 0.6052}\left(\frac{D}{u}\right)^{1/2} \quad (5)$$

Considering average values of temperature during the dew period, r_b is simplified to:

$$r_b = 307\left(\frac{D}{u}\right)^{1/2} \quad (6)$$

The model divides r_b by 2, considering two sides of the sensor in parallel. 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 0.6 mm. The model simply treated the rain interception using measured rainfall amount and a fixed maximum amount of water in the rain reservoir (0.6 mm). This simplification ignores the effect of rainfall rate on interception, but does not lead to serious errors since the maximum intercepted water amount is very small.

For LE estimates at the weather station where the wetness sensor is at the same level as the T, RH and u sensors (Fig. 1), the additional resistance (r_a) is not required, then Eq. (1) can be re-written as follows:

$$\mathrm{LE} = -\frac{\{sR_n + [1200(e_s - e_a)/(r_b)]\}}{s + \gamma^*} \tag{7}$$

For LE estimates at other levels (30 and 110 cm) below 190 cm, which was the height of T, RH and u sensors, Z_T, the specific r_a for each case was determined by calculating the resistance from the turfgrass to each level from Eq. (8) and then finding the differences between appropriate resistance pairs as shown in Fig. 2.

$$r_a = \frac{\ln[(Z_S - d)/Z_O]}{0.4u^*} \tag{8}$$

where Z_S is the height of the wetness sensor (m), d displacement height (=0.65 Z_c), Z_O roughness length (=0.13 Z_c), being Z_C crop height (=0.1 m), and u^* is friction velocity (m s^{-1}), which is given by the log wind profile (Monteith and Unsworth, 1990):

$$u^* = \frac{0.4u_{Z_T}}{\ln[(Z_T - d)/Z_O]} \tag{9}$$

where u_{Z_T} is the wind speed at Z_T from the nearby weather station (m s^{-1}). The following equations resulted:

$$r_{a_{30\,\mathrm{cm}}} = \frac{68.75}{u} \tag{10}$$

$$r_{a_{110\,\mathrm{cm}}} = \frac{19.79}{u} \tag{11}$$

For calculating the friction velocity (u^*) no stability correction was applied since data on vertical temperature differences were not available. It probably accounted for some of the bad performance of the model at 30 cm in comparison to screen height but a sensitive test (results not showed) proved that it is not a serious problem.

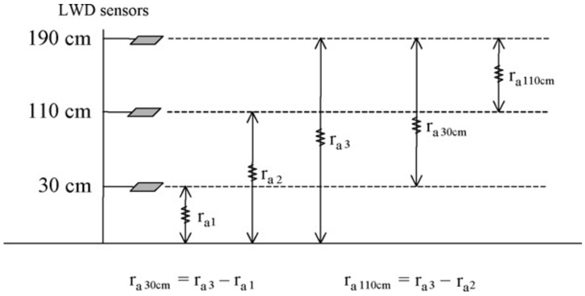

Fig. 2. Schematic representation showing calculation of the aerodynamic resistances (r_a) required to estimate LE by a Penman–Monteith model for 30 and 110 cm over turfgrass.

Using the same procedure adopted by Pedro and Gillespie (1982a,b), wetness onset and dry-off in this model was considered as:

(a) wetness onset: occurs when LE > 0 or rain begins;
(b) wetness dry-off: occurs when the condensation and/or rain accumulated by the model is consumed by an equivalent amount of evaporation.

"Reference" LWD, in hours, was computed as one-quarter of the number of 15-min intervals, from 12:01 h of day n to 12:00 h of day $n + 1$, when the model estimated wetness presence. As an example, if for a given period from 12:01 h of day 1 to 12:00 h of day 2, the sum of 15-min intervals with wetness presence was 37, LWD would be 37 divided by 4, resulting in 9.25 or 9 h and 15 min.

2.4. *Crop leaf wetness duration and wetness coefficient*

Crop leaf wetness duration was estimated by adopting a two-step procedure similar to that recommended by FAO for estimating crop evapotranspiration (Allen et al., 1998):

$$\mathrm{LWD_c} = \mathrm{LWD_r}W \tag{12}$$

where LWD$_c$ is the adjusted crop wetness duration, LWD$_r$ "reference" leaf wetness duration, estimated by the Penman–Monteith approach for a sensor at 30-cm height over turfgrass, and W is the wetness coefficient. The wetness coefficient is the ratio of the crop LWD to the "reference" LWD, and it was determined both for each crop and all crops combined. The effects of characteristics that distinguish the crop surface from the "reference" surface, and the errors in LWD estimates caused by shortcomings of the P–M model, are integrated into W. The LWD$_r$ estimated for 30-cm-height over turfgrass condition was adopted as a "reference", considering the results presented by Sentelhas et al. (2004b).

2.5. *Data analysis*

To evaluate the performance of the Penman–Monteith approach to modeling LWD in a "reference" condition, LWD data measured over mowed turfgrass at 30, 110 and 190 cm heights at Elora during 2003 were used. Weather data from the nearby automatic station installed over turfgrass were used to estimate "reference" LWD by a P–M model according to equations presented in Section 2.3. For estimating LWD at 190 cm, LE was calculated using Eq. (7). For estimating LWD at 30 and 110 cm, LE was calculated using Eq. (1) and r_a values for these heights were obtained using Eqs. (10) and (11), respectively. Measured and estimated "reference" LWD were compared. The use of a P–M model to estimate "reference" LWD for 30-cm height was also evaluated using measured LWD data obtained in Elora, in 2004, in Jundiaí, in 2003/2004, and in Piracicaba, in 2003.

Crop LWD measured near the top of the five crop canopies (coffee, grape, maize, soybean and tomato) were compared to measured and estimated "reference" LWD. Based on the relationship between crop (measured) and "reference" (estimated) LWD, an empirical wetness coefficient (*W*) was determined considering individual crops (specific *W*) and all crops combined (general *W*). Estimated crop LWD was obtained from the product of *W* and estimated "reference" LWD (Eq. (12)), and results were correlated to measured crop LWD.

To validate the two-step procedure to estimate crop LWD, independent LWD and weather data were used. These data were obtained from four other experiments with apple (2000 and 2001), cotton (2005/2006), grape (2005/2006), and muskmelon (2003). Crop LWD estimated by using a general *W* for all these crops, and by using a specific *W* for grape, were correlated to measured crop LWD.

All analyzes mentioned above were done considering regression analysis, for comparison between measured and estimated data, and the following errors: mean error (ME), which describes the direction of the error bias, mean absolute error (MAE), which indicates the magnitude of the average error, and maximum absolute error (MAXE).

3. Results

3.1. Evaluation of a Penman–Monteith approach to estimate "reference" LWD

LWD measurements over turfgrass at three different heights (30, 110, and 190 cm) in Elora during 2003 were used to evaluate the Penman–Monteith approach to estimate "reference" LWD. The relationships between

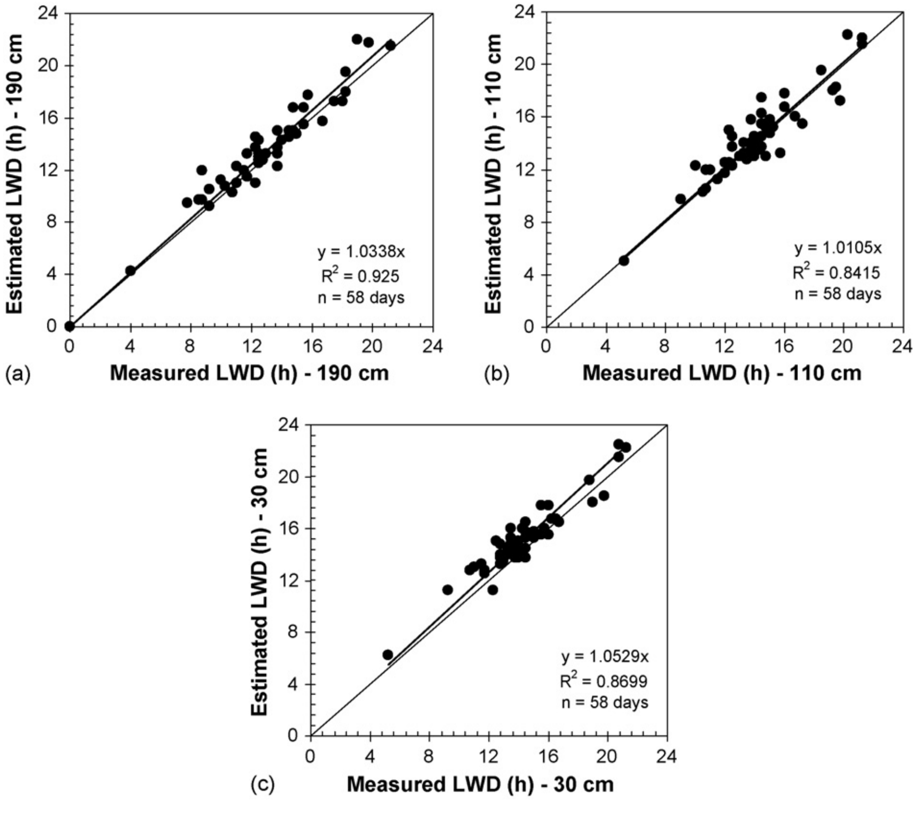

Fig. 3. Relationship between "reference" LWD measured at different heights over turfgrass (a) 190 cm; (b) 110 cm; (c) 30 cm and "reference" LWD estimated for these levels by a Penman–Monteith model, in Elora, during the summer of 2003.

measured and estimated "reference" LWD for the mentioned heights are presented at Fig. 3. A Penman–Monteith approach was able to estimate sensor LWD over turfgrass with good accuracy and precision for all heights, even those (30 and 110 cm) where an additional aerodynamic resistance was required to estimate wetness duration. The model overestimated LWD by 3.3% at 190 cm ($R^2 = 0.92$), 1.5% at 110 cm ($R^2 = 0.87$), and 5.7% at 30 cm ($R^2 = 0.89$).

Errors associated with LWD estimation by the P–M model at different heights are presented in Tables 2 and 3. Table 2 presents the errors of the P–M model for the timing of wetness onset and dry-off, whereas Table 3 presents the errors for LWD estimates. Considering all conditions evaluated, the errors in the time of wetness dry-off were similar among heights, with a tendency for the model to estimate dry-off occurrence later than it was measured. The error was around 40 min for all days, 25 min when considering only days with wetness promoted by dew (without rain), and 60 min when considering only days when wetness was promoted by dew and rain (with rain) (Table 2).

For wetness onset, model-estimated errors were smaller than for wetness dry-off, and differences among heights were observed. For all days and days without rain, MAE for onset increased with decreasing sensor height, whereas for days with rain, the error associated with wetness onset remained around 25 min for all heights. In general, the model tended to estimate wetness onset late for sensors at 110 and 190 cm and early for the sensor at 30 cm, except for days with rain when late wetness onsets were observed for all heights. One possible reason for lateness of estimates on rainy days is related to the difference in sensitivity to rain onset between a wetness sensor and a rain gauge. The sensor will detect the rain onset almost immediately, whereas the gauge (which triggers rain wetness in the model) records onset only at the first tip after 0.254 mm of precipitation.

Table 2
Mean error (ME) and mean absolute error (MAE) for timing of occurrence of wetness onset and dry-off estimated by a Penman–Monteith model at different heights over mowed turfgrass at Elora, Ontario, Canada, during 2003

Sensor height (cm)	Wetness onset		Wetness dry-off	
	ME (min)	MAE (min)	ME (min)	MAE (min)
All days[a]				
190	+6	19	+32	39
110	+6	25	+21	37
30	−18	30	+28	38
Days without rain[b]				
190	+4	16	+19	25
110	+2	23	+10	27
30	−28	33	+18	25
Days with rain[c]				
190	+9	23	+54	63
110	+13	28	+39	55
30	+1	24	+44	62

[a] Days when wetness was promoted only by dew or by dew and rain.
[b] Days when wetness was promoted only by dew.
[c] Days when wetness was promoted by dew and rain.

Table 3
Mean error (ME), mean absolute error (MAE) and maximum absolute error (MAXE) for LWD estimated by a Penman–Monteith model at different heights over mowed turfgrass at Elora, Ontario, Canada, during 2003

Sensor height (cm)	ME (h)	MAE (h)	MAXE (h)
190	+0.47	0.76	3.25
110	+0.20	0.89	3.00
30	+0.78	1.05	2.50

The P–M model overestimated LWD for all heights, with MAE increasing from 190- to 30-cm height (Table 3). The overestimation was on average between 0.75 and 1.08 h. The MAXE was between 2.5 and 3.25 h.

Using results from the experiments in Elora (2004), Jundiaí (2003/2004), and Piracicaba (2003) (Fig. 4), but considering only LWD measured and estimated at 30 cm above turfgrass, the tendency of overestimation by the P–M model was also observed. In this case, the

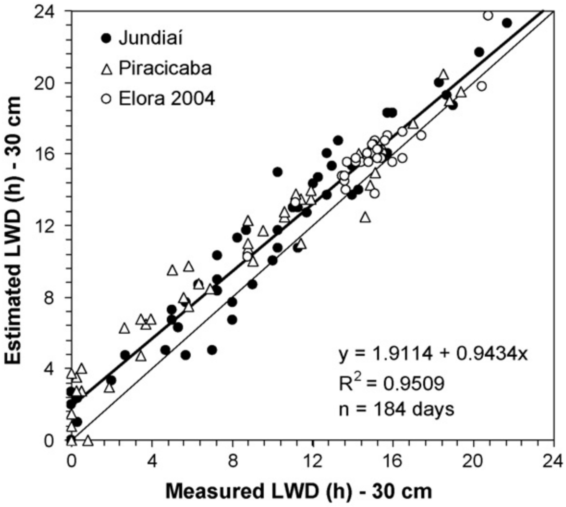

Fig. 4. Relationship between "reference" LWD measured at 30-cm height over turfgrass and "reference" LWD estimated for the same height by a Penman–Monteith model, in Elora (2004), Jundiaí (2003/2004), and Piracicaba (2003).

Table 4
Mean error (ME), mean absolute error (MAE) and maximum absolute error (MAXE) for LWD estimated by a Penman–Monteith model for 30-cm height in Elora, Ontario, Canada in 2004, Jundiaí and Piracicaba, in São Paulo State, Brazil

Location	ME (h)	MAE (h)	MAXE (h)
Elora (2004)	+0.86	1.08	3.00
Jundiaí	+1.29	1.55	4.70
Piracicaba	+1.74	1.92	4.50
General	+1.33	1.55	4.70

model, in average, overestimated LWD by 6.9% ($R^2 = 0.92$) and overestimation was greater at smaller values of LWD (Fig. 4). Errors in onset and drying time are probably not strongly dependent on the duration of wetness, and these timing errors become relatively a smaller fraction of LWD as wetness period increases, so that the LWD estimation accuracy is likely to be greater for longer wetness periods. For these comparisons, the overall MAE was 1.55 h and MAXE was 4.70 h (Table 4).

3.2. Measured crop LWD versus "reference" LWD

Following Sentelhas et al. (2004b, 2005), we correlated measured crop LWD with both measured and estimated "reference" LWD (Fig. 5).

The relationship between measured crop and measured "reference" LWD for five crops (coffee, grape, maize, soybean, and tomato) showed very good agreement, with slope = 0.9942 and $R^2 = 0.9656$ (Fig. 5a). This reinforces the idea that a nearby sensor over turfgrass is a good option to estimate crop LWD and therefore adopting a physically based model to estimate LWD at height of 30 cm over turfgrass is a viable alternative to a direct determination of crop LWD. However, when crop LWD was correlated with modeled "reference" LWD, estimated by the P–M model (Fig. 5b), the same tendency of overestimation previously observed for turfgrass (Fig. 4) was obtained, on average 6.3% ($R^2 = 0.92$), with greater errors at smaller values of LWD. As the shorter wetness periods are caused by dew, the model overestimation might be associated with the difficulty of measuring low wind speeds at night. Under such conditions when the anemometer may stall, average recorded wind speed may be too small. This makes r_a and r_b too big, and modeled dew starts early. This problem is not an error in the model itself and could be fixed with an empirical correction.

As the LWD overestimation caused by the P–M model was observed for all five crops studied, one simple solution is to apply an empirical wetness coefficient to convert "reference" LWD into crop LWD, similar to that used by FAO (Allen et al., 1998) to convert reference into crop evapotranspiration.

3.3. Wetness coefficient (W) and crop LWD

As the LWD errors caused by the P–M model decreased with increasing wetness duration (Fig. 5b), *W* varied according to estimated "reference" LWD, increasing with hours of wetness in an asymptotic curve. Figs. 6 and 7 present *W* curves for all crops combined (general *W*) and for each specific crop (specific *W*) respectively. For all crops, specific *W* values were very similar (Fig. 7), but there were some differences in corrections for wetness onset and in the asymptotic values reached at 24 h.

When a general *W* (Fig. 6) was used to convert "reference" LWD into crop LWD, the tendency of crop LWD overestimation disappeared and a very good

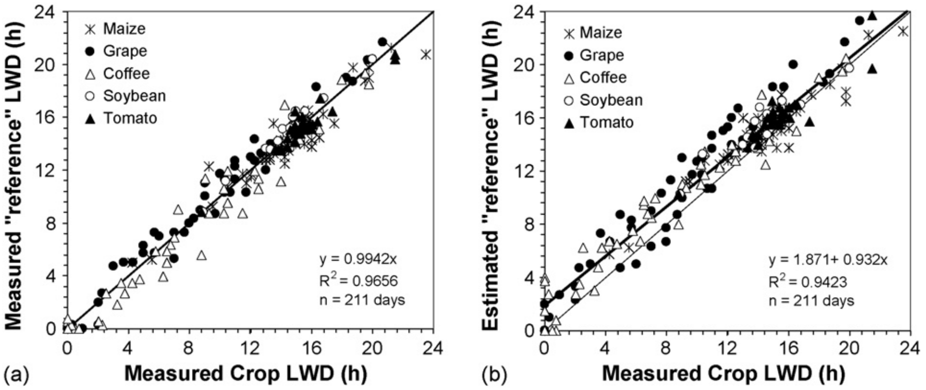

Fig. 5. Relationship between crop LWD measured at the top of different crop canopies and: (a) "reference" LWD measured at 30-cm height over turfgrass and (b) "reference" LWD estimated by a Penman–Monteith model for 30-cm height above turfgrass.

agreement between measured and estimated crop LWD was established (Fig. 8a), with slope = 1.0049 and $R^2 = 0.9448$, even considering the differences in crop height and architecture. The MAE associated with crop LWD estimates was 0.91 h (Table 5). The best crop LWD estimates were obtained for soybean and tomato with an MAE of only 33 and 35 min, respectively, and MAXE no greater than 2.5 h.

The use of a specific W for each crop (Fig. 7) did not change the agreement very much between measured and estimated crop LWD compared to the use of a general W, with a slope = 0.9947 (Fig. 8b). However, a slight improvement in the precision of the estimates was observed, with R^2 improving to 0.9541 (Fig. 8a versus b). The use of a specific W coefficient for each crop

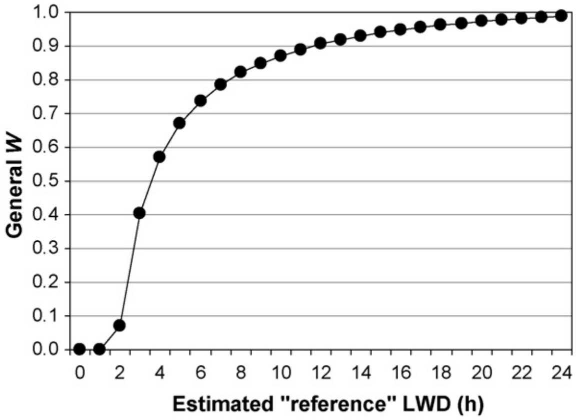

Fig. 6. General wetness coefficient (general W) used to convert "reference" LWD into crop LWD.

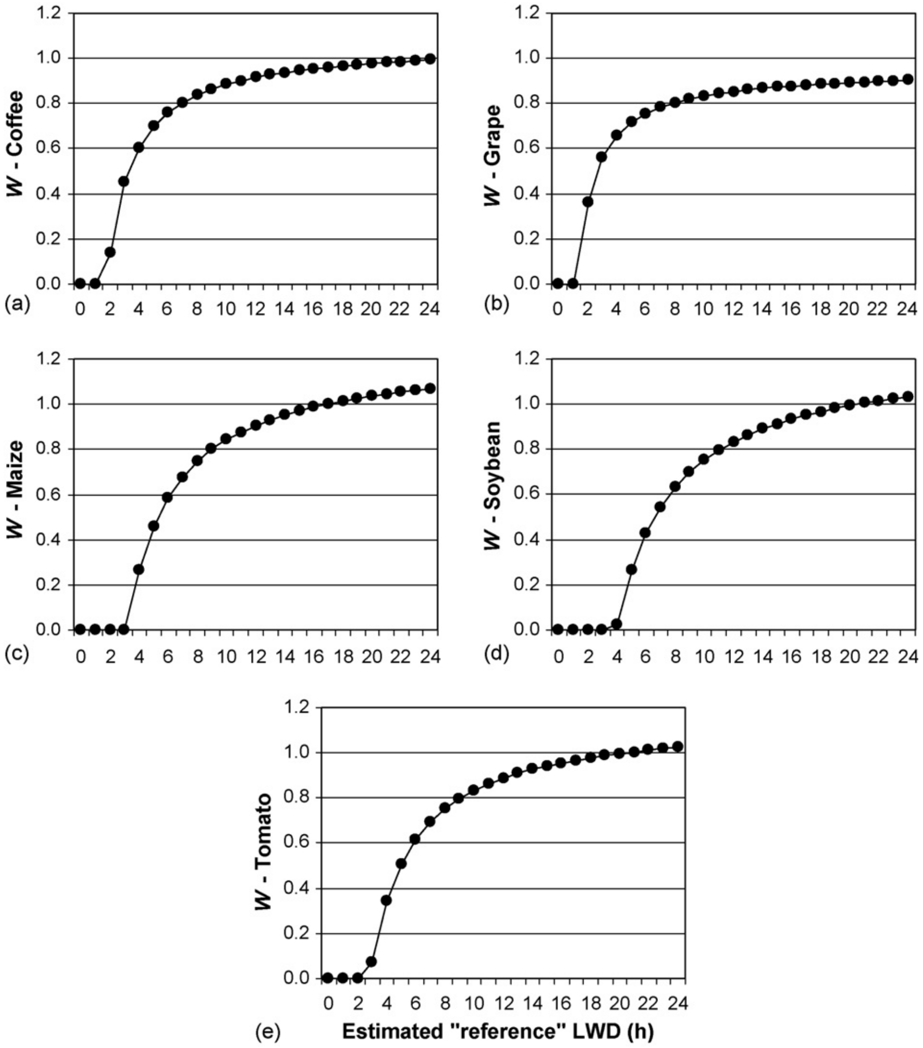

Fig. 7. Specific wetness coefficient (specific W) for five different crops: (a) coffee, (b) grape, (c) maize, (d) soybean, and (e) tomato, to convert "reference" LWD into crop LWD.

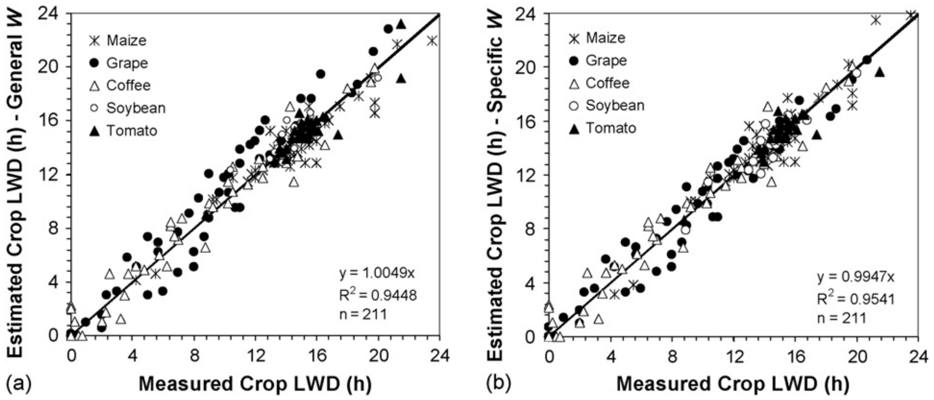

Fig. 8. Crop LWD estimated by multiplying estimated "reference" LWD by (a) general *W* and (b) specific *W* coefficients compared to the LWD measured at the top of five different crop canopies: coffee (Piracicaba, 2003), grape (Jundiaí, 2003/2004), maize (Elora, 2003), soybean and tomato (Elora, 2004).

reduced the MAE to 0.84 h and the MAXE to 3.04 h (Table 5). The best crop LWD estimates were obtained for soybean and tomato crops, but the best improvement using a specific *W* was observed for the grape crop, with MAE falling from 1.38 to 1.08 h and MAXE from 3.29 to 2.84 h (Table 5).

3.4. Estimating crop LWD with independent data

As the previous analysis was done with the same data that generated the *W* values, the two-step procedure to estimate crop LWD was also tested with independent data. The use of a specific *W* was tested for grape while general *W* was tested for apple, cotton, grape, and muskmelon.

Table 5
Mean error (ME), mean absolute error (MAE) and maximum absolute error (MAXE) for crop LWD estimated by a Penman–Monteith model, when using general and specific *W* coefficients for coffee, grape, maize, soybean, and tomato

Crop	ME (h)	MAE (h)	MAXE (h)
General *W*			
Coffee	+0.13	0.99	2.99
Grape	+0.63	1.38	3.29
Maize	−0.37	0.82	3.18
Soybean	+0.37	0.59	1.95
Tomato	−0.05	0.55	2.41
General	+0.13	0.91	3.29
Specific *W*			
Coffee	+0.17	1.01	3.01
Grape	−0.07	1.08	2.84
Maize	−0.09	0.81	3.04
Soybean	−0.09	0.54	1.73
Tomato	+0.04	0.59	2.76
General	+0.01	0.84	3.04

When a specific *W* for grape was used, the relationship between measured and estimated crop LWD was very good, with a slope of 0.9862 and $R^2 = 0.90$ (Fig. 9a). The mean absolute error associated with the crop LWD estimates was 1.25 h (Table 6). When the general *W* was used to estimate crop LWD for apple, cotton, grape and muskmelon, the same precision ($R^2 = 0.90$) and accuracy (slope = 1.0377) was observed (Fig. 9b) as well as the same magnitude of the errors. MAE ranged from 1.22 h for apple to 1.61 h for cotton, and the overall MAE, considering all crops combined, was 1.31 h (Table 6).

4. Discussion

Our results showed that a Penman–Monteith approach was able to estimate "reference" LWD over turfgrass at different heights with high accuracy and precision at Elora (Fig. 3 and Tables 2 and 3). The comparison between estimates and measurements showed mean absolute errors of around 1 h, which are similar to those obtained with other physical models by Pedro and Gillespie (1982a,b) and Francl and Panigrahi (1997), and smaller than those obtained with the same model by Rao et al. (1998), of 1.8 h, and Sentelhas et al. (2004a), of 2 h. MAE values obtained with similar physical model by Lou and Goudriaan (2000) were around 2.1 h, by Madeira et al. (2002) were around 1.5 h, and by Dalla Marta et al. (2005) were around 2.3 h. The P–M model had a similar error magnitude to models used by Pedro and Gillespie (1982a,b), but has the advantage of not requiring temperature data at the crop level. When the P–M model was used to estimate "reference" LWD (at 30-cm height) at three different locations (Fig. 4 and Table 4),

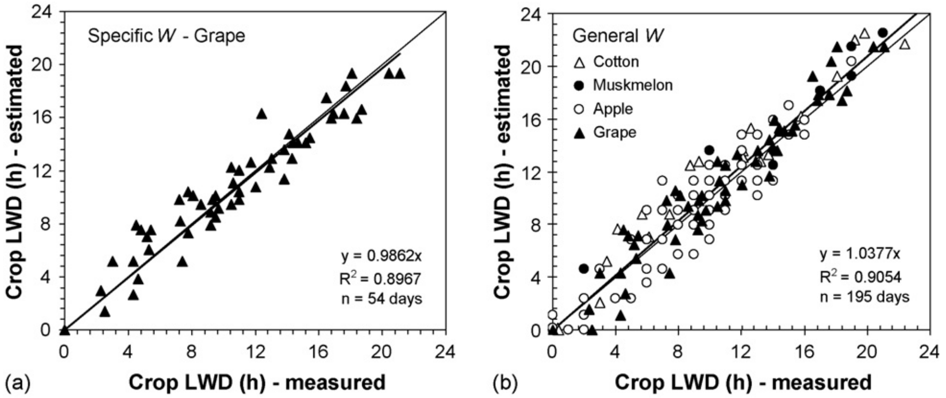

Fig. 9. Crop LWD estimated by multiplying estimated "reference" LWD by: (a) specific *W* and (b) general *W* coefficients (data independent from the determination of *W*) compared to LWD measured at the top of four different crop canopies: apple (Ames, 2000/2001), cotton (Piracicaba, 2005/06), grape (Jundiaí, 2005/06), and muskmelon (Ames, 2003).

the magnitude of the errors increased but still remained smaller than 2 h, which is within the range of errors obtained by other physical models. A possible source of error for estimating LWD by the P–M model is the net radiation data, which is measured for horizontal surfaces although the sensor is not exposed horizontally, considering that it has a better performance with and angle between 30° and 45° to horizontal (Sentelhas et al., 2004b). Positive R_n values over a flat plate tilted down and facing poleward will usually be smaller than R_n measured over the turfgrass or crop surface, while at night R_n over a tilted flat plate will be a little less negative than R_n measured on a horizontal surface. This issue will be investigated in our ongoing studies.

Based on results presented by Sentelhas et al. (2004b), we elected the sensor deployed over turfgrass at 30-cm height as our standard for "reference" LWD. The correlation between this measured "reference" and crop LWD, presented in Fig. 5a, showed that our suggestion of estimating crop LWD from measured "reference" LWD is valid; especially for crops where the longest LWD is observed at the top of the canopy, as reported by Sentelhas et al. (2005) for five different height-architecture crop canopies (apple, coffee, grape, maize, muskmelon). In this case, when "reference" LWD is measured, the *W* value to convert "reference" into crop LWD is 1. Based on these findings, we modeled LWD on a 30 cm sensor and correlated this estimated "reference" LWD with measured LWD from five crops combined (Fig. 5b) and obtained a definite relationship. However, the overestimation of crop LWD by modeled "reference" LWD remained, with an average error of about 6.3%.

To reduce the overestimation, a simple and practical alternative was to use an empirical wetness coefficient (*W*) to convert P–M "reference" LWD into crop LWD. *W* values ranged from 0 to 0.99, for all crops combined, and from 0 to 0.90–1.07, when each crop was considered individually. These values were dependent on the "reference" LWD magnitude, which means that this coefficient is related mainly to the weather conditions. Crop type, height and architecture showed little influence on *W* values, since *W* curves had similar shapes, as also happens with K_c values used to convert reference to crop ET (Allen et al., 1998). The results showed an improvement of the crop LWD estimates when both general and specific *W* corrections were used (Fig. 8 and Table 5), with a very slight overestimation (ME < +0.13 h), and average absolute errors smaller than 1 h. These errors are of the same magnitude as other physical models used to estimate crop LWD, which require more specific data for each crop such as air temperature at leaf level (Pedro and Gillespie,

Table 6
Mean error (ME), mean absolute error (MAE) and maximum absolute error (MAXE) for crop LWD estimated with independent data by a Penman–Monteith model, when using a specific *W* coefficient for grape, and the general *W* coefficient for apple, cotton, grape, and muskmelon

Crop	ME (h)	MAE (h)	MAXE (h)
Specific *W*			
Grape	+0.10	1.25	3.91
General *W*			
Apple	+0.03	1.22	4.33
Cotton	+1.34	1.61	3.77
Grape	+0.33	1.26	3.36
Muskmelon	+1.02	1.46	3.62
General	+0.40	1.31	4.33

1982a,b) or net radiation above and below the canopy and leaf area (Magarey, 1999; Magarey et al., 2005; Dalla Marta et al., 2005).

When independent data were used to test our proposition to estimate crop LWD, we observed that both general and specific W coefficients gave very good performance, with very small deviations from a 1:1 line. The ME value was +0.10 h when a specific W was used for a grape canopy, and ranged from +0.03 to +1.34 h when a general W was used for four different crops, MAE was smaller then 1.61 h for all conditions analyzed, and MAXE was no greater than 4.33 h. Our proposition performed very well for new data from one of the same crops (grape) used to generate W values, as well as for three different crops, apple, cotton and muskmelon. This allows us to state that W is not influenced very much by crop type when the objective is to estimate LWD at the top of the crop canopies.

Considering that the upper canopy is the position of the crop where the longest leaf wetness usually occurs in the climates we have studied (Sentelhas et al., 2005), our proposition for adopting a two-step method of estimating LWD, similar to the FAO ET-system, showed high potential for practical application in crop disease management. The use of a specific W for each crop was better, but our results showed that crop LWD estimated with both specific and general W was good enough to be used in warning systems to control plant diseases, with the advantage of using only weather data available from a nearby weather station.

5. Conclusions

A Penman–Monteith approach was able to estimate ‘‘reference’’ LWD over turfgrass at different heights with high accuracy and precision. When compared to LWD measured in five crops with different heights and architecture, 30-cm height ‘‘reference’’ LWD estimated by a P–M model showed promise as a simple and useful tool to estimate crop LWD. When an empirical coefficient (W) was applied in a two-step procedure to convert estimated ‘‘reference’’ into crop LWD, a significant improvement in crop LWD estimates was observed. In this system, the use of a specific W for each crop is recommended, but even a general W allowed us to estimate crop LWD with high accuracy and precision to be used in diseases warning schedules. More studies are required to test and validate this technique for other crops, especially for those where the longest LWD does not occur at the top of the crop canopy.

Acknowledgements

This project was funded in part by a fellowship to the first author from Brazilian Council for Research and Development (CNPq-Proc. 202536/02-5), and by USDA. Authors wish to thank Jean C. Batzer and Sara Helland, from Iowa State University, and Eduardo A. Santos and Jorge Lulu, from ESALQ, University of São Paulo, for providing part of the LWD and weather data used in this study.

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