EVALUATION OF A PENMAN-MONTEITH APPROACH TO PROVIDE "REFERENCE" AND CROP CANOPY LEAF WETNESS DURATION ESTIMATES

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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. 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. 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 hour per 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 hours when both general and specific *W* coefficients were used.

Key words: Dew, Rain, Physical model, Plant disease, Warning system.

Introduction: Leaf wetness is recognized as a very important weather parameter for plant disease epidemiology (Huber and Gillespie, 1992). 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. Because LWD is not widely measured, several methods have been developed to estimate it from weather data (Pedro and Gillespie, 1982, Huber and Gillespie, 1992; Rao et al., 1998; 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. 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, 1982). 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 from several authors have shown that Penman-Monteith approaches estimated LWD very well under diverse climatic conditions. Considering that, 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; and b) Assess the ability of an empirical wetness coefficient (*W*) to convert "reference" LWD into crop LWD.

Material and methods: Leaf wetness duration measurements over turfgrass and at the top of the crop canopies were done with painted 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. Each LWD sensor was mounted on a section of PVC or metal tubing, with an inclination angle of 30^o or 45^o and installed in the field. The field experiments were conducted on turfgrass and eight crops at four different locations: Elora, Ontario, Canada (43^o49' N, 80^o35' W) – turfgrass, maize, soybean, and tomato; Piracicaba, São Paulo State, Brazil (22^o42' S, 47^o30' W) – turfgrass, coffee, and cotton; Jundiaí, São Paulo State, Brazil (23^o06' S, 46^o55' W) – turfgrass and table-grape; Ames, Iowa State, U.S.A. (42^o01' N, 93^o46' W) – turfgrass, muskmelon, and apple. In each location, a nearby standard automatic weather station, installed over turfgrass, measured: air temperature (T), relative humidity (RH), wind speed (u), and net radiation (Rn). 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. Using the same procedure adopted by Pedro and Gillespie (1982), 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. 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): LWDc = LWDr * W, where LWDc = adjusted crop wetness duration, LWDr = "reference" leaf wetness duration, estimated by the Penman-Monteith approach for a sensor at 30-cm height over turfgrass, and *W*= wetness coefficient. 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*. 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. 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 2003/04, 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*). 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 (2005/06), grape (2005/06), and muskmelon (2003).

Results: 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. 1). The comparison between estimates and measurements showed mean absolute errors of around 1 hour, which are similar to those obtained with other physical models by Pedro and Gillespie (1982), and smaller than those obtained with the same model by Rao et al. (1998), of 1.8 hours, and Sentelhas et al. (2004), of 2 hours. The P-M model had a similar error magnitude to models used by Pedro and Gillespie (1982), but has the advantage of not requiring temperature data at the crop level.

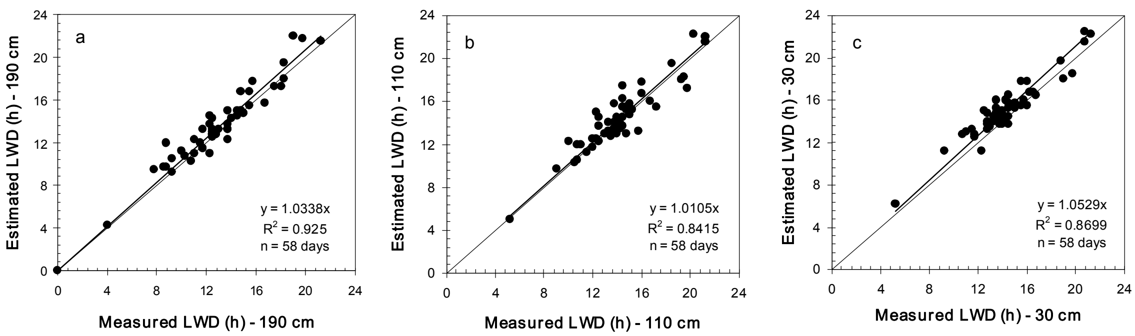

Fig. 1 - Relationship between "reference" LWD measured at different heights over turfgrass (a – 190 cm; b – 110 cm; and c – 30 cm) and "reference" LWD estimated for these levels by a Penman-Monteith model, in Elora, during the summer of 2003.

When the P-M model was used to estimate "reference" LWD (at 30-cm height) at three different locations (Fig 2), the magnitude of the errors increased but still remained smaller than 2 hours, which is within the range of errors obtained by other physical models. The correlation between this measured "reference" and crop LWD, presented in Fig. 3a, 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. 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 3b) 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 Kc 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 (Figs. 8), with a very slight overestimation (Mean Error < +0.13 hours), and average absolute errors smaller than 1 hour.

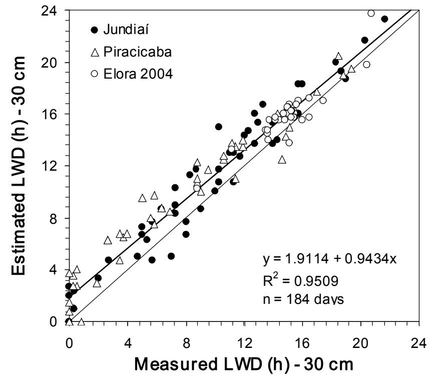

Fig. 2 - Relationship between "reference" LWD measured at 30-cm height over turfgrass and "reference" LWD estimated for the same height by a Penman-Monteith model, in Elora, Jundiaí, and Piracicaba.

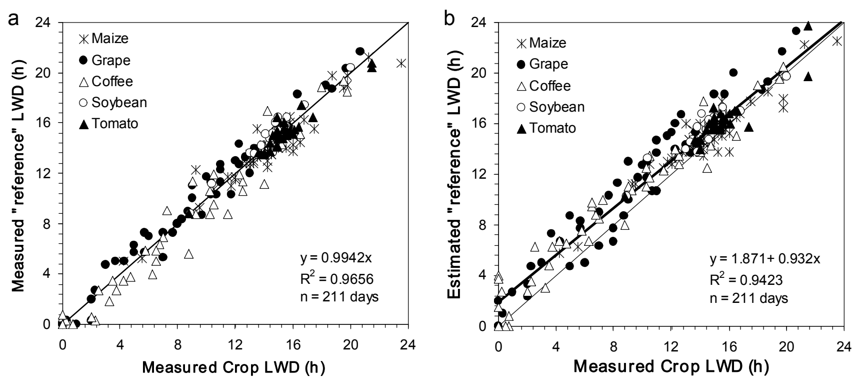

Fig. 3 - Relationship between crop LWD measured at the top of different crop canopies and: a) "reference" LWD measured at 30-cm height over turfgrass and b) "reference" LWD estimated by a Penman-Monteith model for 30-cm height above turfgrass.

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 (Fig. 5). The Mean Error value was +0.10 hours when a specific *W* was used for a grape canopy, and ranged from +0.03 to +1.34 hours when a general *W* was used for four different crops, Mean Absolute Error was smaller then 1.61 hours for all conditions analyzed. 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.

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.

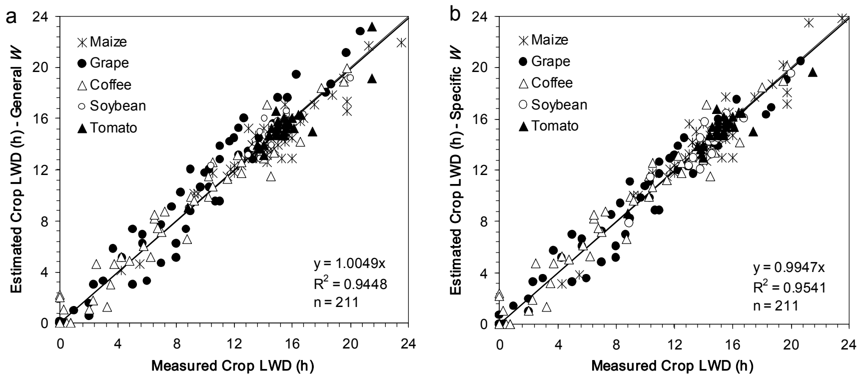

Fig. 4 – Crop LWD estimated by multiplying estimated "reference" LWD by (a) general *W* and (b) specific *W* coefficients compared to the LWD measured at the top of five different crop canopies: coffee (Piracicaba, 2003), grape (Jundiaí, 2003/04), maize (Elora, 2003), soybean and tomato (Elora, 2004).

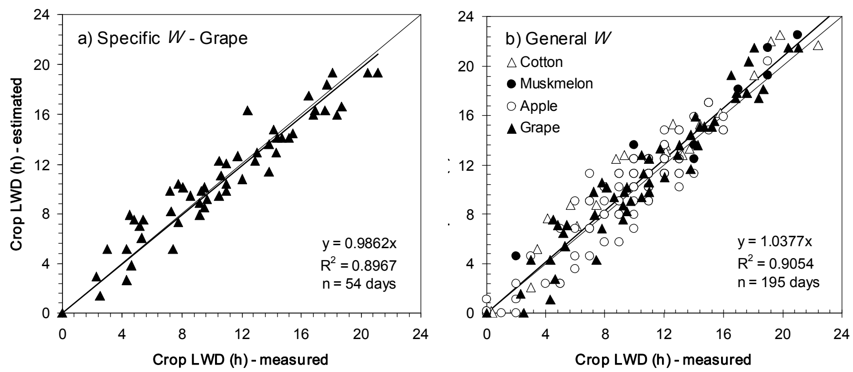

Fig. 5 – Crop LWD estimated by multiplying estimated "reference" LWD by (a) specific *W* and (b) general *W* coefficients (data independent from the determination of *W*) compared to LWD measured at the top of four different crop canopies: apple (Ames, 2000/01), cotton (Piracicaba, 2005/06), grape (Jundiaí, 2005/06), and muskmelon (Ames, 2003).

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