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An Evaluation of Physically Based and Empirically Determined Evapotranspiration Models for Nursery Plants

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Abstract: A lysimeter study was conducted to determine the evapotranspiration (ET) rates of Red Sunset red maple (*Acer Rubrum* 'Red Sunset') nursery trees under outdoor conditions in August and September 1997. The average ET rate was 0.084 mm day^{-1}. This measured ET rate was compared with calculated ET rates based on four physical ET (i.e., Penman, Penman-Monteith, Stanghellini and Fynn) and two empirically determined ET models (vapor pressure deficit (VPD) and solar radiation based empirical ET models). The Penman-Monteith and Penman models overestimated the measured ET rate by 15% and 31%, respectively while the Stanghellini and Fynn models underestimated the measured ET rates by 19.7% and 16.3% with R^2 values of 0.70, 0.582, 0.645 and 0.644, respectively. The linear regression analyses showed that the single variables solar radiation and vapor pressure deficit each correlated with ET and R^2 values of 0.750 and 0.650 respectively. This study showed that VPD or solar radiation based empirical ET models could be used to predict ET rates of nursery plants if there is difficulty in running the physically based ET model due to a lack of input parameters.

Key Words: Transpiration, evapotranspiration, nursery production, combination models

Fiziksel Temelli ve Ampirik Bitki Su Tüketimi Modellerinin Fidan Bitkisi İçin Değerlendirilmesi

Özet: Kırmızı akçaağaç bitkisinin evapotranspirasyonunu (ET) belirlemek amacıyla tarla koşullarında bir lizimetre çalışması yürütülmüştür. Ağustos ve Eylül 1997 yılında yapılan bu çalışmada ortalama bitki su tüketimi 0.084 mm $gün^{-1}$ olarak belirlenmiştir. Ölçülen ET; Penman, Penman-Monteith, Stanghellini, Fynn matematiksel modelleri ile havanın buhar açığı ve solar radyasyonu içeren ampirik ET modeli ile karşılaştırılmıştır. Penman-Monteith ve Penman modelleri ölçülen evapotranspirasyonu sırasıyla %15 ve %31 oranında fazla tahmin ederken, Stanghellini ve Fynn modelleri ise sırasıyla %19.7 ve %16.3 oranında düşük tahmin etmiştir. Penman-Monteith, Penman, Stanghellini ve Fynn modellerinin regrasyon katsayıları (R^2) sırasıyla 0.700, 0.582, 0.645 ve 0.644 olarak tespit edilmiştir. Solar radyasyon ve havanın buhar açığı ile ölçülen ET arasındaki regrasyon katsayıları sırasıyla 0.750 ve 0.650 olarak bulunmuştur. Bu çalışma, havanın buhar açığı veya solar radyasyonu kullanan ampirik eşitliklerinin input girdilerinin bulunmasında zorluk çekilen matematiksel modellerin yerine ET tahmininde kullanılabilirliğini göstermiştir.

Anahtar Sözcükler: Transpirasyon, Evapotranspirasyon, Fidan üretimi, kombinasyon modeli

Introduction

Water use by crops is of increasing concern as demands for water are growing while supplies are not. Evapotranspiration (ET) is the total amount of water lost via plant transpiration and soil evaporation per unit soil area where a crop is growing, in the unit of L / T or L^3 / L^2T. Reference evapotranspiration, ET_o, is often defined as the ET of a broad expanse of 0.10 to 0.15 m tall, cool-season grass when the ET is not limited by soil water content. The ET_o is used to quantify evaporative demand within a region and to estimate crop ET when the ET_o is multiplied by a crop coefficient (K_c) factor to account for differences between the grass and crop ET (Allen et al., 1998; Schuch and Burger, 1997). Keach (1998) and Ventura et al. (1999) stated that evaporation occurs from all open surfaces whenever there is sufficient energy for latent heat of vaporization as well as vapor pressure deficit. Transpiration involves the movement of water from a soil medium into plant roots, up through stems into leaves, followed by evaporation from leaves into the atmosphere. Because it is difficult to separate plant transpiration from soil evaporation, and because larger plants lose water mostly through transpiration, evaporation and transpiration are generally grouped together as ET. Two essential driving forces for transpiration to occur are solar radiation and a vapor pressure gradient. If soil moisture is adequate, plant characteristics and local climatic factors determine the rate of plant transpiration.

Weighing lysimeters are one of the most accurate devices for directly measuring ET and calibrating ET equations, especially for container grown plants. They can measure the mass fluctuations of moisture in container mediums at precise time intervals, accounting for both rainfall and irrigation while measuring the amount of water lost through ET. Advances in electronic instrumentation and data logging have allowed accurate, high-resolution measurements with these lysimeters (Olmsted, 1990). Water depleted from the soil by ET must be replenished in arid and semi-arid regions by irrigation for successful crop production. Direct measurement of ET is difficult and costly. Hence, there are many different approaches to estimating ET indirectly from either empirical models or physically based models using easily obtained meteorological data (Wright and Jensen, 1987).

The objective of this study was to determine the capability of four physically based models to predict evapotranspiration in comparison to two empirical models. The most representative ET models would ultimately provide a basis for computer-controlled irrigation and fertigation.

Materials and Methods

This study was conducted at the Ohio Agricultural Research Development Center (OARDC), Wooster, Ohio (41° 48 N' latitude) in August and September of 1997. Red Sunset red maple (*Acer Rubrum* 'Red Sunset') trees, one of the most common nursery trees grown in Ohio landscapes and nurseries, were used for this study. The trees acquired were 1.25 m tall "whips", potted in 26.5 L containers, and spaced on a 1.8 × 1.8 m grid in an outdoor laboratory. A schematic view of the experimental setup is shown in Figure 1.

Drip irrigation lines included a 130-micron (120 mesh) filter and a 300 kPa pressure regulator. Polyethylene tubing (16 mm) was used to distribute either water or a water/nutrient recipe to each container through a 1 m Netafim regulated spray stake assembly (Netafim Irrigation, Inc., Fresno, CA 93727) composed of

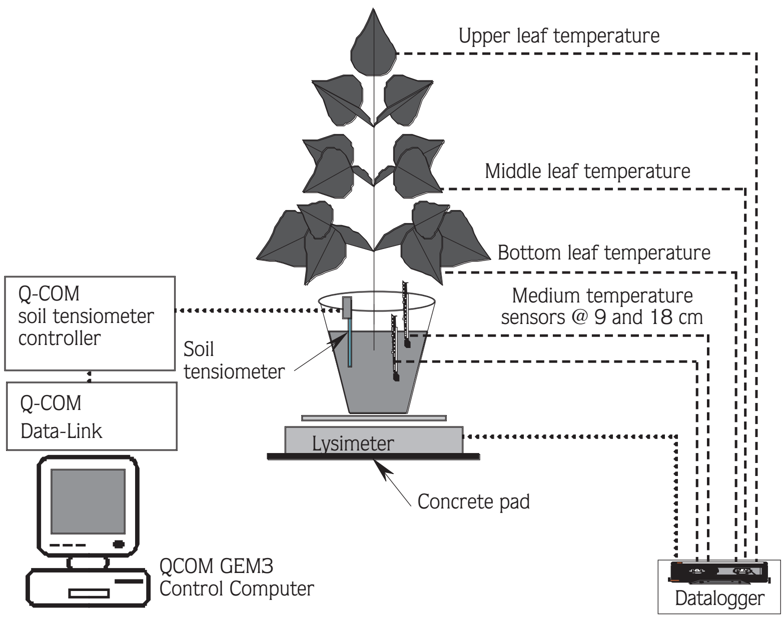

Figure 1. Schematic drawing of instrumental setup for Acer Rubrum.

3 mm spaghetti tubing and emitters calibrated to deliver 0.19 L min^{-1}. Osmocote slow release fertilizer (8-9 months) with N-P-K percentages of 18-6-12 (The Scotts Company, Marysville, OH 43041) was used to fertilize the plants using an automatic fertigation system. Irrigation was done automatically based on soil-water tension using local city water. The tension in the potting medium was not allowed to go above a maximum of 12 kPa in order to avoid water stress (Short et al., 1997). The Q-COM GEM3V2 computer control system was used to monitor soil-water tension. In order to measure evapotranspiration, a Sartorius F330S automatic weighing scale (Sartorius GmbH, Gottingen, Germany) with a resolution of ±1 g was placed beneath the tree containers as shown in Figure 1. The leaf temperature was measured using type T thermocouples (0.127 mm D) inserted into central veins located on the underside of selected leaves. The study was conducted for only August and September, not for the whole growing season, since the plant water consumption was at the maximum level in these months due to higher solar radiation. All required meteorological data were obtained from an automatic recording weather station located adjacent to the nursery. The leaf area index (LAI) was defined as the ratio of total leaf area of a plant to the top projected canopy area (TPCA) of the plant. The LAI was calculated as 1.58.

Physically and empirically based models

Physically based models for predicting ET have been developed and revised over the past half century. The physically based ET models that were used in this study were those of Penman (1948), Penman-Monteith (1965), Stanghellini (1987) and Fynn (1993). The first such model was introduced by Penman (1948), in which he used energy balance to predict evaporation from crop surfaces. He accounted for the energy required for evaporation, and he also recognized the need to account for the aerodynamic energy (wind) required for the removal of water vapor from leaf surfaces. Thus his equation became known as the "combination equation". The model was tested using well-watered grass as a reference crop. However, it did not include surface resistance and aerodynamic resistance adjustments for water vapor transfer. Resistances to heat and water vapor transfer were differentiated between the external resistance, controlling the movement of vapor from the leaf surface to the free air, and the internal resistance, which is a function of the characteristics of the leaf cuticle layer and the stomata. Rijtema (1965) and Monteith (1965) independently accounted for this surface and aerodynamic resistance in appraising evaporation rate. As a result, the so-called Penman-Monteith (P-M) equation was defined.

Stanghellini (1987) made an extensive evaluation of the P-M equation in subsequent research. This study concluded that an irradiative resistance to heat transfer needed to be accounted for. The combination equation also needed revision to account for conditions in a greenhouse, where air velocities are typically less than 1.0 $m.s^{-1}$. The Stanghellini combination equation includes the surface and aerodynamic resistance terms as well as a modified calculation of the radiation heat flux at the canopy based on the short-wave irradiance. Stanghellini used a leaf area index (LAI) to account for energy exchange from multiple layers of leaves on greenhouse plants. Finally, Fynn (1993) used a derivation similar to Stanghellini's to achieve a combination equation for ET in a greenhouse. His equation is distinguished by using total net radiation rather than Stanghellini's modified radiation calculation. The Fynn equation is also different because it modifies only the vapor pressure term with the LAI since water vapor exchange occurs at all layers of the canopy, while the irradiative energy exchange only occurs in the top most layer. Table 1 shows the formulas of all the models used in the study. Table 2 shows the terms used in each of the combination equations. The soil heat flux, or energy storage term as it is described in Fynn (1993), was considered negligible where it was used in these equations.

The following expressions define the variable terms in each equation:

$$\lambda = 2502535.259 - (2385.76 \times T_a) \tag{5}$$

$$\delta = 41.45 \times \exp(0.06088 \times T_a) \tag{6}$$

$$\rho_a = \frac{100000}{(287 \times (T_a + 273.15))} \tag{7}$$

$$\ln(e_a^*) = \frac{-1044}{T_a} - 11.29 - 0.02702\, T_a + 1.289 \times 10^{-5}\, T_a^2 - 2.478 \times 10^{-9}\, T_a^3 + 6.546 \ln T_a \tag{8}$$

Table 1. List of equations for physically based evapotranspiration models.

Name	Equation	No.
Penman	$LE = \frac{\delta}{\delta+\gamma}(R_n - G) + \frac{\gamma}{\delta+\gamma} 6.43\,(1.0 + 0.53U_2)(e_a^* - e_a)$	(1)
P-M	$LE = \frac{\delta}{\delta+\gamma^*}(R_n - G) + \frac{\gamma}{\delta+\gamma^*} \rho_a \lambda (e_a^* - e_a) \div r_e$	(2)
Stanghellini	$LE = \frac{2.LAI.\rho_a.c_p}{1 + \frac{\delta}{\gamma} + \frac{r_i}{r_e}} \left[0.07 \frac{\delta}{\gamma} \frac{I_s}{\rho_a c_p} + 0.16 \frac{\delta}{\lambda} \frac{T_a - T_o}{r_R} + \frac{1}{r_e} \frac{e_a^* - e_a}{\gamma}\right]$	(3)
Fynn	$ET = \frac{2.LAI.\rho_a c_p \left[e_a^* - e_a\right] / r_e + \delta (R_n - G)}{\lambda \gamma r_i}$	(4)

Table 2. Explanation of terms in the four physically based models evaluated in this study.

Terms	Symbol
Latent heat flux density (Wm^{-2})	LE
Psychometric constant (Pa °C^{-1})	γ
Latent heat of vaporization of water (Jkg^{-1})	λ
Net raditation (Wm^{-2})	R_n
Soil heat flux (Wm^{-2})	G
Slope of the saturation vapor pressure-temperature curve (Pa °C^{-1})	δ
Wind velocity at 2 m above the canopy (ms^{-1})	U_2
Saturation vapor pressure at mean air temperature(Pa)	e_a^*
Vapor pressure of the air (Pa)	e_a
Ambient air temperature (°C)	T_a
Temperature at the leaf surface (°C)	T_o
Relative humidity	RH
Air specific heat at constant pressure(Jkg^{-1} °C^{-1})	c_p
Air density (kgm^{-3})	ρ_a
External resistance of canopy to sensible heat (sm^{-1})	r_e
Internal resistance of canopy to vapor transfer (sm^{-1})	r_i
Radiation heat transfer resistance (sm^{-1})	r_R
Shortwave irradiance ($Wm^{-2}v$)	I_s
Leaf area index (m^2m^{-2})	LAI

$$e_a = e_a^* \text{ x RH} \qquad (9)$$

$$\gamma = c_p/\lambda \text{ and } \gamma^* = \gamma\left(1 + \frac{r_i}{r_e}\right) \qquad (10)$$

In order to find the ET rate in the Penman, P-M, and Stanghellini models, latent heat flux density calculated was divided by latent heat of water vaporation. For all ET calculation methods, internal and external resistances (ri and re) for the canopy were chosen to be 70 $s.m^{-1}$ and 50 $s.m^{-1}$ respectively, while the radiation resistance (r_R) used in the Stanghellini model was assumed to be 200 $s.m^{-1}$ (Short et al., 1999). ET was measured hourly by lysimeter as mass losses while irrigation and precipitation were measured as mass gains. Losses in mass were compared to calculated ET rates using the Penman, P-M, Stanghellini and Fynn models.

In order to evaluate the individual and combined effects of climate factors on the measured ET, linear multiple regression analyses were done with Minitab in order to determine empirically based ET models. To do that, nonsignificant terms were eliminated one by one from the model and a new regression model was set up each time until all variables in the model became significant at a 90% confidence level. By doing this backward elimination, the final simple order model consisted of solar radiation, vapor pressure deficit (VPD) and leaf temperature. However, since it is difficult for nursery growers to measure leaf temperature practically, leaf temperature was eliminated from the models. Hence, two empirically based ET models (radiation-measured ET and VPD-measured ET) were obtained with an R^2 of 0.75 and 0.65, respectively as below:

$$ET = 0.20\ Rs + 25.084 \tag{11}$$

$$ET = 0.075\ VPD + 28.179 \tag{12}$$

The RMSE statistic was used to compare ET_0 estimates with lysimeter measurements. The RMSE provides a good measure of how closely the two independent data sets match. The RMSE values were calculated as

$$RMSE = \left(\sum_{i=1}^{N} \frac{1}{N} (P_i - O_i)^2\right)^{0.5} \tag{13}$$

where N is the number of observations, P_i is the predicted ET_0 value, and O_i is the corresponding measured ET value.

Results and Discussion

Leaf and air temperatures, wind speed, solar radiation, VPD and measured transpiration could be plotted for any 24-hour period. Two example 24-hour plots are shown in Figures 2 and 3. One is a typical sunny day and one is a typical cloudy day. The plots show that the highest transpiration levels occurred during the middle of the day when air and leaf temperatures and radiation were all at maximum levels and relative humidity was low. Generally, the top leaves were the most irradiated and cooler than the lower leaves. The top leaf canopy absorbed most of the solar radiation and therefore reduced evaporative cooling for the middle and bottom leaves. Leaf temperatures were similar for early morning and late night when there was limited transpiration and limited solar radiation. The average difference between leaf temperature and air temperature was about 2 ºC due to evaporative cooling during high transpiration rates for midday conditions.

The RMSE values of Penman, P-M, Fynn and Stanghellini models were 0.068, 0.040, 0.050 and 0.049 mm day^{-1}, respectively. These findings were also supported by Howell et al. (1998), who concluded that the P-M model resulted in the lowest RMSE for field

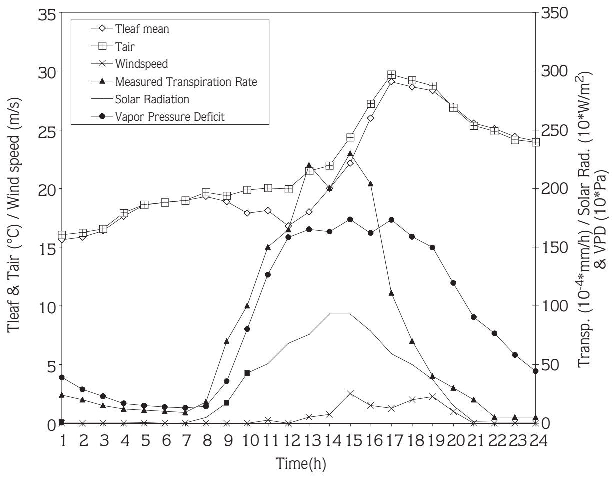

Figure 2. Air temperature, wind speed, measured transpiration and solar radiation, and VPD for Red Maple on a sunny day (14/8/1997).

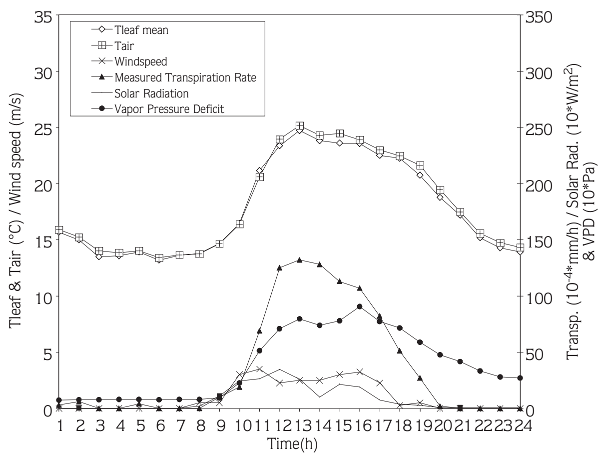

Figure 3. Air temperature, wind speed, measured transpiration and solar radiation, and VPD for Red Maple on a cloudy day (12/9/1997).

crops compared to Penman type models. Our results also supported statements made by Venture et al. (1999), who concluded that Penman models having calibrated wind functions often fail in locations with a climate different from that where they were calibrated. However, the P-M type equations should be less affected by this phenomenon because canopy resistance rather than wind function is calibrated. There was good correlation between the single variable VPD and measured transpiration rate and the single variable solar radiation and measured transpiration rate (Figures 4 and 5). These results confirmed the findings of Short et al. (1997) and Fynn et al. (1993). They mentioned that when there is sufficient water in the soil or container medium and stomata are fully open, atmospheric conditions control the transpiration rate. During early morning, VPD, solar radiation and transpiration were all very low. As the solar radiation increased, transpiration was more responsive to solar radiation than VPD (Figures 4 and 5). During the middle of the day, VPD, solar radiation and transpiration were all at the highest rates. In the late afternoon, when solar radiation was decreasing, the driving force for transpiration tended to be VPD. Using the coefficient of determination (R^2) as calculated from a simple linear regression analysis over two months of continuous hourly data (excluding all night time data), it was evident that solar radiation with a coefficient of 0.750 was more correlated to ET than VPD with a coefficient of 0.650 (Figures 4 and 5). Table 3 shows that the correlations between calculated and measured hourly ET rates of red maple, excluding all nighttime data, for the Penman, P-M, Stanghellini and Fynn ET models were 0.582, 0.70, 0.645 and 0.644, respectively. Although the Penman model was developed mainly for outside conditions and had a wind factor in the formula, its R^2 value was the lowest. This lack of correlation for the Penman model may be explained by the fact that it includes no resistance terms. The average of all lysimeter measurements of daily ET recorded during the two-month period August and September (61 days) was 0.084 mm day^{-1}.

The average ET rates as calculated using the Penman, P-M, Stanghellini and Fynn models were 0.11, 0.097, 0.067 and 0.070 mm day^{-1}, respectively. Our results showed that the empirically based ET models made better predictions than the physically based ET models. This can be explained by the fact that the empirically based ET models represent the environmental conditions, which drive the ET, in a much better way than the physically based ET models do. As mentioned by Kirnak (1998), the empirical approach uses regression analysis to identify correlations between input parameters and transpiration rate. The weakness of this approach is that empirical formulae developed for a specific region during a specific time period may not always be used accurately for other time periods and regions. Physically based models that are based on energy balances typically provide a more comprehensive estimate of transpiration. However, the disadvantage of these models is that they have data requirements that may often be unavailable or immeasurable.

The Penman and P-M ET models overestimated the measured ET by 31.0% and 15%, respectively. On the other hand, the Stanghellini and the Fynn ET models underestimated the measured ET by 19.74% and 16.32%, respectively. The P-M model was best in terms of error and R^2 value among the four physical ET models. Since transpiration occurs mainly during the daytime, all nighttime data (8:00 pm-5:00 am) was excluded from the statistical analysis to avoid any misleading comparisons of ET models.

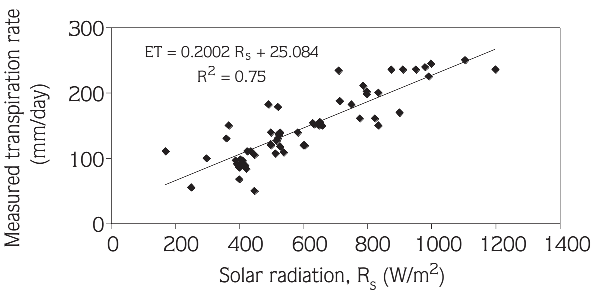

Figure 4. Correlation between solar radiation and measured ET rate for two months of hourly data excluding all nighttime data.

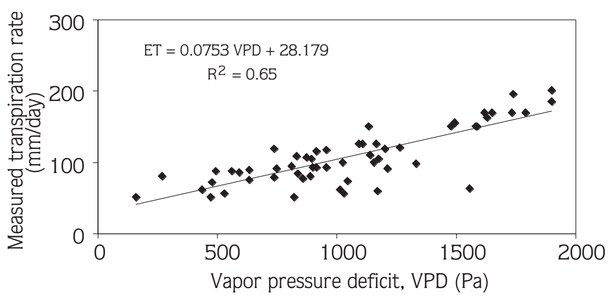

Figure 5. Correlation between VPD and measured ET rate for two months of hourly data excluding all nighttime data.

Table 3. Linear regression analysis of four physically based ET models with R^2 and RMSE (mm day^{-1}) values.

Physically based ET models	Linear equation	R^2	RMSE
Penman	ET = 0.9668 x + 42.539	0.582	0.068
P-M	ET = 1.0341 x + 37.677	0.700	0.040
Stanghellini	ET = 0.7976 x + 12.094	0.645	0.049
Fynn	ET = 0.7335 x + 11.329	0.644	0.050

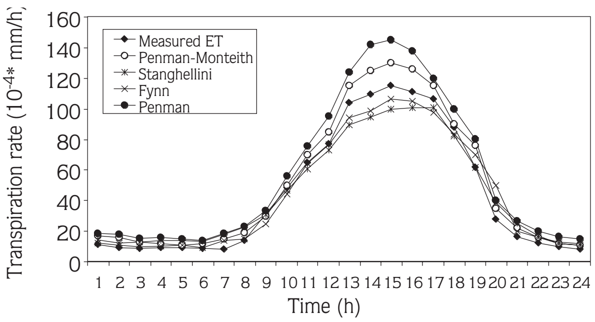

Figure 6. Average hourly transpiration rate for different ET models for two months of experimental data.

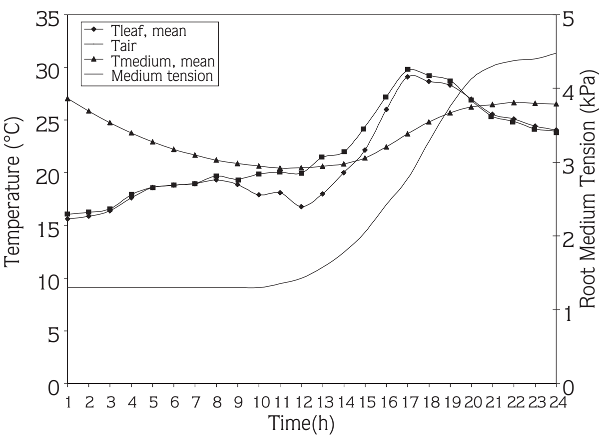

Figure 7. Typical air, leaf, root medium temperature and root medium tension variations for a clear day (14/8/1997).

Figure 6 shows the average hourly transpiration rate calculated from the three ET models compared to measured ET during the two-month experimental period. It was observed that the Stanghellini and Fynn methods estimated the transpiration rate to be 16 to 20% lower than the measured ET during the middle of the day, whereas they estimated the transpiration rate higher than the measured ET during the morning and late afternoon. The Penman and P-M models overestimated ET, especially during high transpiration periods, while the Fynn and Stanghellini models underestimated ET during high transpiration periods. Figures 7 and 8 show the air, leaf and container medium temperature and soil-water tension variations for a clear day (14/8/97) and a cloudy day (12/9/97). Average container medium temperatures deviated 1.5 to 2 °C from the mean during the experimental period. The temperature of the container medium at any time depended on the ratio of the energy absorbed to that being lost.

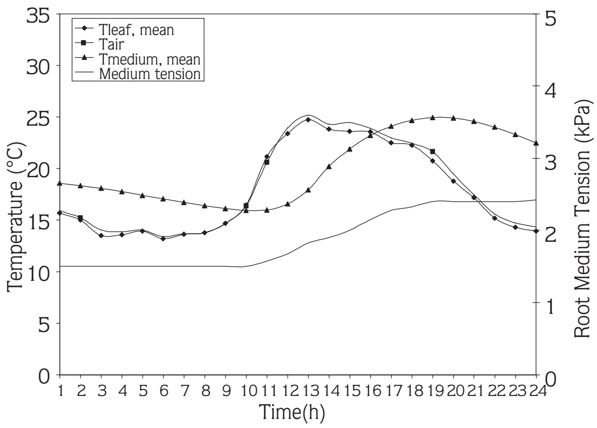

Figure 8. Typical air, leaf, root medium temperature and root medium tension variations for a cloudy day (12/9/1997).

A visual observation of the data indicated that container medium temperature variations near the surface were high compared to those at lower depths for the clear day and vice versa for the cloudy day. On clear days, temperatures near the surface layer did not reach their maximum until some time after solar noon. On cloudy days, variations in container medium temperature during early morning and late night were very close to each other due to low incoming solar radiation. Overall, the variations on cloudy days were very small compared to those on clear days. Another visual observation was that container medium moisture content had a significant influence on medium temperature. High medium moisture levels led to small temperature changes due to its high specific heat. This supported the idea of Keach (1998) that moisture control in soil has more influence on soil temperature than any other soil management practice such as mulching.

Conclusions

This study used meteorological measurements from nursery trees to predict ET, using both physically based and simple linear regression models. In all it appeared that the empirical models did at least as well if not better than the physically based models. Results of the linear regression analysis emphasized that there was high correlation between solar radiation, VPD and measured ET. The P-M model estimated ET with less error and a higher R^2 value compared to other ET models. The Penman and P-M methods estimated the ET rates higher than the measured ET throughout the 24-hour period while the Stanghellini and Fynn models underestimated them.

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