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A Comparison Between Deterministic and Stochastic Evapotranspiration Models for Container Grown *Acer Rubrum*

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Abstract

A lysimeter study was conducted to determine evapotranspiration (ET) rates of Red Maple (*Acer Rubrum*) under field conditions in Columbus-OH, USA. The average daily measured ET for the plant for two months including all night time data was 998.75 g. This measured ET was compared against Fynn, Stanghellini and Penman's evapotranspiration models. Fynn and Stanghellini ET model underestimated actual ET rates by 16.32 and 19.74% respectively but Penman model overestimated actual ET rate by 30.99% when excluding night time data and/or data less than 50 g/tree h. R^2 values of Fynn, Stanghellini and Penman ET model were 0.644, 0.645 and 0.582 respectively. Simple linear regression analyses showed that a solar radiation or a VPD based stochastic ET model could be successfully used to predict ET in terms of R^2 value of 0.758 and 0.647 respectively.

Key Words: Acer Rubrum, transpiration, evapotranspiration, combination models, stochastic ET models.

Saksıda Yetiştirilen *Acer Rubrum* Bitkisi için Matematiksel ve Stokastik Evapotranspirasyon Modellerinin Karşılaştırılması

Özet

ABD Columbus-OHIO'da arazi koşullarında kırmızı akçaağaç'ın (Acer Rubrum) evapotranspirasyon (ET) oranını belirleyebilmek için bir lizimetre çalışması gerçekleştirilmiştir. Tüm gece süresini de içeren 2 aylık süre boyunca ölçülen günlük ortalama ET değeri 998,75 g bulunmuştur. Ölçülen bu ET değeri Fynn, Stanghellini ve Penman ET modelleri ile karşılaştırılmıştır. Fynn ve Stanghellini ET modelleri gerçek ET'yi sırasıyla %16,32 ve %19,74 oranlarında daha az tahmin etmiş, Penman modeli ise gece verileri ve/veya 50 g/ağaç saat'ten daha az olan verileri çıkardığımızda %30,99 oranında fazla tahmin etmiştir. Fynn, Stanghellini ve Penman ET modellerinin R^2 değerleri sırasıyla 0.644, 0.645 ve 0.582 olarak bulunmuştur. Basit lineer regresyon analizleri solar radyasyon ve VPD tabanlı stokastik ET modelinin ET tahminlerinde başarılı bir şekilde kullanılabileceğini göstermiştir.

Anahtar Kelimeler: Acer Rubrum, transpirasyon, evapotranspirasyon, kombinasyon modeller, stokastik ET modeller.

INTRODUCTION

Since ET is a very important process for intensive crop production, environmental quality, cost, as well as water and nutrient conservation, many researchers have conducted studies to quantify ET including [1, 2,]. As a result, many complex methods have been developed to compute transpiration based on climatological parameters such as temperature, solar radiation, wind speed and relative humidity and also plant characteristics such as leaf area index, and stomatal resistance. However, all these models are criticized for being computationally difficult and data intensive allowing many opportunities for errors. So, it is desirable to develop reliable, simple, inexpensive and practical methods for the estimation of ET in proportion to vapor pressure deficit (VPD) or solar radiation inputs [3,4]

Measurement of ET has been used almost entirely for research applications due to the required equipment complexity and cost. Therefore, the prediction of ET from meteorological data is potentially more useful since the measurement of weather parameters is much easier than the measurement of ET. Furthermore, recent advances in sensor and datalogger technology permit accurate and easy measurement of on-site weather data.

Evapotranspiration is the combined total amount of water lost via transpiration and evaporation from the soil and plant surfaces. Evaporation occurs from all open surfaces whenever there is sufficient energy for latent heat of vaporization. Transpiration involves movement of water from soil into plant roots, transport of the water through stems into leaves, and evaporation of the water from leaves into the atmosphere. Because it is difficult to determine each loss rate precisely; and, because larger plants lose water mostly by transpiration, they are generally grouped together as evapotranspiration [5,6].

Two essential components for transpiration to occur are latent heat of vaporization and a vapor pressure gradient [7]. Transpiration is generally favorable to plants since it aids in absorption and transport of mineral nutrients; it also cools the leaves during radiant periods due to the latent heat of vaporization. Too much transpiration, however, can result in stress, and most plants have mechanisms for diminishing transpiration when necessary, including reduction in leaf area by rolling of leaves or by changing leaf orientation (wilting) to reduce intercepted solar radiation [5]. Transpiration, however, is affected more by the meteorological conditions than by plant characteristics [8].

Weighing lysimeters are one of the most accurate devices for directly measuring ET and calibrating ET equations. They measure the mass fluctuations of soil moisture within a mass of soil at precise time intervals while accounting for amount of water added to soil via rainfall or irrigation, or the amount lost through ET. Advances in electronic instrumentation and datalogging have allowed accurate, high resolution measurements in weighing lysimeters [9,10].

[11] pointed out that an effective lysimeter should be a representative sample of the larger environment and larger group of plants. For instance, when lysimeters are used in container nurseries, conditions of the soil and plant should be the same for the lysimeter plant compared to other plants to diminish errors. Since lysimeters are used to measure ET directly, they are frequently used to evaluate the effect of different climatic factors on ET and to evaluate methods for estimating ET.

Besides direct measurement of ET, there are many different approaches to estimating ET indirectly from empirical or physically-based models using easily obtained meteorological data [12]. The empirical approach uses statistics 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. Using energy balance, physically-based models typically provides a more comprehensive estimate of transpiration. The disadvantages of the physically-based models, however, are that they have extensive data requirements that are often unavailable.

The Fynn and Stanghellini ET models were mainly developed for greenhouse conditions whereas Penman was developed for field conditions. While climatical factors are controlled under greenhouse conditions, it is impossible to control the climate at outside conditions. The main differences between these two conditions in terms of meteorological factor were wind, solar radiation and, precipitation. Because the wind speed generally is lower than 1 m/s in the greenhouse, the effect of the wind under the green house conditions is usually negligible [13].

When there is sufficient water in the soil and stomata are fully open, atmospheric conditions control the transpiration rate. The most important environmental factors affecting the transpiration rate are temperature, humidity, solar radiation, and wind speed [14,15].

Red Maple (*Acer Rubrum*) is one of the most common nursery trees grown in Ohio landscapes and nurseries and considered somewhat difficult to grow. The main objective of this study was to determine the accuracy of the deterministic combination model for predicting ET in comparison to stochastic solar radiation and vapor pressure deficit models.

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. The nursery plant used was *Acer Rubrum* (Red Maple) acquired as 1.25 m tall "whips" and potted in 26.5 L containers. The plants were located on a 1.8 × 1.8 m spacing in the experiment area. The height and diameter of the container was 30 cm and 35 cm respectively and the medium depth of soil mix in the container was 20 cm. A Schematic of the experimental setup is shown in Figure 1.

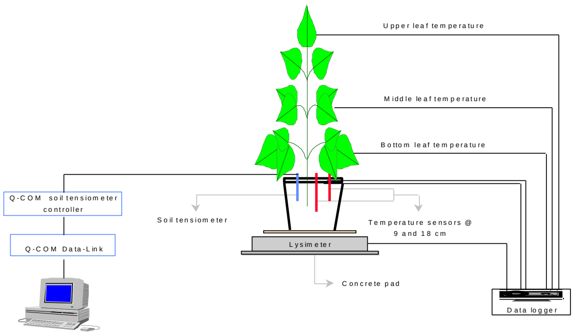


Figure 1. Schematic drawing of experimental setup for Red Maple.

The potting medium used in the experiment, Metro Mix 510 (The Scotts Company, Marysville, OH), was common to the nursery industry and recommended for its good physical and chemical characteristics. It was especially noted for excellent aeration and rapid water percolation. It was also compatible with drip emitters and the microirrigation system. A slow release fertilizer called Osmocote (8-9 month) was used to fertilize half the plants and experimental formulations were injected into the fertigation system for the other plants. N-P-K ratio of the Osmocote was 18-6-12.

Since salinity levels of irrigation water and potting medium may affect ET, the nutrient content of the growing medium was analyzed. Results showed that the salinity level of the medium was normal based on its pH (pH=7.2) and electrical conductivity (EC=3.0 mmho/cm). According to normally accepted standards, a normal soil must have a pH between 6.5 and 7.2 and an EC value less than 4 mmho/cm [16].

The water source for irrigation was local city water with a pH and soluble salts (electrical conductivity) of 7.2 and 0.53 mmhos/cm respectively. This range of pH and EC for the irrigation water was within acceptable water quality standards with a pH between 6.5 - 8.4 and an EC value less than 0.75 mmhos/cm.

Meteorological data (ambient temperature, wind speed, wind direction, relative humidity, barometric pressure, and radiation) were obtained from an automatic recording weather station located adjacent to the nursery growing area. All measurement sensors on the weather station were connected to the Q-COM Inc., Irvine, CA computer control system and continuously stored in GEM3V2 software at 15 minutes interval. Rainfall was measured manually using rain gages located at three different places in the experimental area.

Potting media tension was allowed to go up to maximum 21 kPa and irrigation was done manually by considering the tension levels and observing cumulative water loss with the weighing lysimeter. Sampling interval for medium tension was 15 minutes. Hourly average values were used to represent meteorological variables and medium tension in the statistical analysis and A Q-COM computer with GEM3V2 software was used to sense the medium tension.

In order to measure ET, A SATORIUS F330S automatic weighing scale with an accuracy of ±1 g was placed beneath one of the tree containers as shown in Figure 1. The lysimeter readings were recorded in print and cassette by using a Kaye DIGISTRIP III datalogger. Instantaneous weight readings were also displayed digitally in grams by the SATORIUS A/D converter.

While five climate parameters (ambient temperature, leaf temperature, wind speed, relative humidity, and solar radiation) and LAI were required to use the most complex theoretical ET estimation methods, soil temperature and potting medium tension were also collected to evaluate the potential effects of each on transpiration rates. The leaf temperature was measured from upper, middle and bottom parts of the plant and averaged. Each leaf temperature was measured using type T thermocouples of 0.127 mm size inserted into the central veins from the underside of the leaf. Since the thermocouples were easily removed from the vein due to wind, an adhesive band was used for holding them in place. The datalogger recorded leaf and medium temperature readings in 15 minutes intervals.

The potting medium temperature was measured at two different depths within the root volume. Two potting medium temperature sensors were 9 ± 0.5 cm deep and 18 ± 0.5 cm deep and averaged. The soil temperature sensors were type T, ungrounded, 1/8″ stainless steel probes. These sensors were calibrated with ice in the lab before the experiment.

Each tensiometer was calibrated before use by using a long plastic u-tube and a meter stick using a C-clamp. After the u-tube was filled with water, one end was attached securely to the pressure transducer in order to prevent leakage in the seal between the tube and the transducer. Then, the differential water head readings from u-tube and Q-COM controller were matched to each other. If there was no match between these two readings, adjustments were made on the Q-COM software.

The leaf area index (LAI) was an input parameter for many ET equations. It was defined as the ratio of total leaf area of a plant to the projected horizontal ground area of the plant canopy. In this study, a total of 10 leaves were removed from different parts of the plant and then measured as a basis for determining the average leaf area. An electronic areameter was used to measure each sample leaf. The areameter was calibrated based on known areas of metal plates. The horizontally projected area of the plant was calculated assuming a rectangular shape resulting in a LAI of 1.58.

Tree stem diameter was measured approximately 15 cm above the top of each pot. The height and radial orientation of the measurements were marked so that later measurements for determining growth could be made at the same location and orientation. Average canopy height and stem diameter for trees used in this study were approximately 1.62 m and 15.15 mm respectively. At the end of a two months experimental period, these values were approximately 1.88 m and 19.80 mm respectively.

Deterministic Transpiration Calculation Methods

Penman, Fynn and Stanghellini deterministic ET calculation methods were used.first derived the combination equation for computing the ET by considering the aerodynamic and energy budget equations that are required for evaporation and removing the vapor. The main advantage of the Penman equation was that the measurement of the leaf temperature was unnecessary. Penman tested the equation using well-watered grass as a reference crop. The Penman combination equation is as follow:

$$\lambda E = \frac{\Delta}{\Delta+\gamma}\left(R_n - G\right) + \frac{\gamma}{\Delta+\gamma} 6.43(1.0 + 0.53U_2)(e^{o}_{z} - e_z) \quad (1)$$

where

λE = Latent heat flux density (MJ. m^{-2}. d^{-1})

Δ = Slope of the saturation vapor pressure curve versus air temperature (kPa/^oC)

R_n = Net radiation (MJ .m^{-2}.d^{-1})

G = Soil heat flux (MJ. m^{-2}.d^{-1}).

γ = Psychometric constant (kPa/^oC)

U_2 = Wind velocity at 2 meter (m/s)

e_z^o = Saturation vapor pressure at mean air temperature (kPa)

e_z = Vapor pressure of the air (kPa).

[1, 2] both modified the combination equation to calculate transpiration under the greenhouse conditions. Although both Fynn and Stanghellini models developed using thermodynamic energy balance theory (Eq. 2 and Eq. 3 respectively), there are some differences between these two models. Fynn model uses a generalized resistance terms whereas Stanghellini uses a more detailed resistance terms. Besides, Fynn model considers the effects of energy stored in the canopy. Fynn model also uses only ambient air temperature whereas Stanghellini uses both ambient air and canopy leaf temperature [13]. Because climatical factors for outside conditions, especially wind and solar radiation may be different from the greenhouse, the accuracy of the Fynn and Stanghelline equations are evaluated.

$$ET = \frac{2LAI\ .\rho.C_p\left[e_s(T_a) - e(T_a)\right]/r_w + \delta\left(Q_{RAD} - Q_G\right)}{L_v\,\gamma r_c} \quad (2)$$

where

ET = ET rate (Kg.m^{-2}.s^{-1})

L_v = Latent heat of vaporization of water (J.kg^{-1})

Q_G = Rate that energy is stored in the canopy (J/m^2.s)

Q_{RAD} = Irradiance absorption rate by the canopy (J/m^2.s)

ρ = Air density (kg/m^3)

C_p = Specific heat of air at constant pressure (J/kg. ^oC)

$e(T_a)$ = Vapor pressure at air temperature (Pa)

r_w = Air resistance for water vapor transfer (s/m)

$e_s(T_a)$ = Saturation vapor pressure at air temperature (Pa)

LAI = Leaf area index

γ = Psychometric constant (Pa/^oC)

r_c = Crop resistance for water vapor transfer (s/m)

δ = Slope of saturated vapor pressure curve with temperature (Pa/^oC).

$$LE = \frac{2.LAI.\rho_a.c_p}{1 + \frac{\delta}{\gamma} + \frac{r_i}{r_e}}\left[0.07\frac{\delta}{\gamma}\frac{I_s}{\rho_a c_p} + 0.16\frac{\delta}{\lambda}\frac{T_h - T_o}{r_R} + \frac{1}{r_e}\frac{e_a^{*} - e_a}{\gamma}\right] \quad (3)$$

where

LE = Latent heat flux (W.m^{-2})

C_p = Air specific heat at constant pressure (J.Kg^{-1}.C^{-1})

ρ_a = Air density (Kg.m^{-3})

δ = Slope of saturated vapor pressure curve with temperature (Pa.$^oC^{-1}$)

γ = Thermodynamic psychometric constant (Pa.$^oC^{-1}$)

r_e = Transfer resistance of external heat (s.m^{-1})

r_R = Radiation heat transfer resistance (s.m^{-1})

r_I = Transfer resistance of internal heat(s.m^{-1})

I_s = Shortwave irradiance (W.m^{-2})

T_h = Ambient temperature (^oC)

T_o = Temperature at the external surface (^oC)

e^{*}_{a} = Saturation air vapor pressure (Pa)

e_a = Air vapor pressure(Pa)

LAI = Leaf area index (m^2.m^{-2}).

In ET calculation methods, internal and external resistances for the canopy were chosen to be 70 sm^{-1}, 50 sm^{-1}

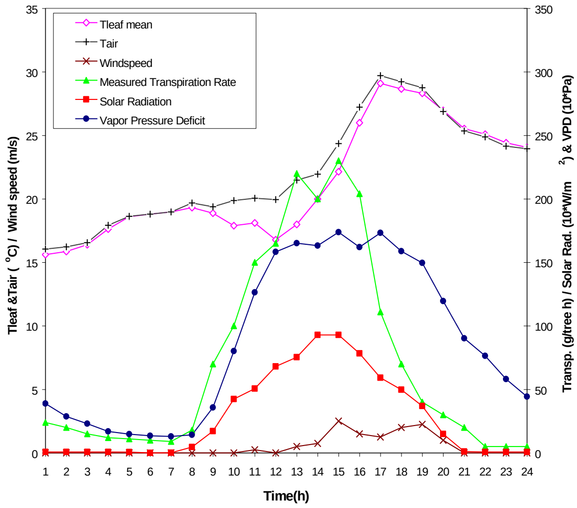
respectively and the radiation resistance used in the Stanghellini model was assumed to be 200 sm^{-1} [17].

Hourly ET was determined as the lysimeter mass losses while considering irrigation and precipitation mass gains. Then, measured results were compared to the Penman, Fynn, and Stanghellini deterministic ET models. In order to evaluate the difference between calculated and measured ET, the following formula was used [18]:

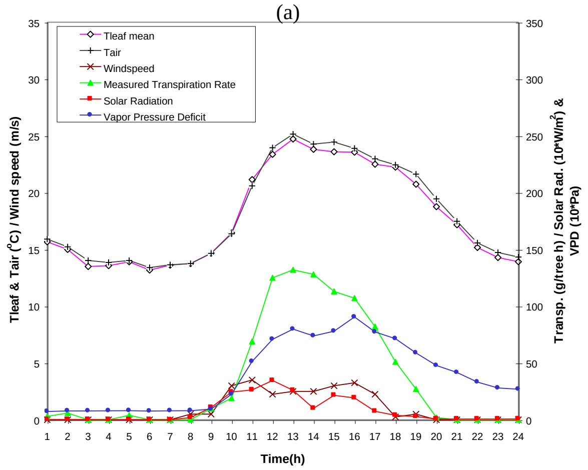
Error = (Calculated ET - Measured ET) / Measured ET (4)

RESULTS and DISCUSSION

Hourly ET rates of *Acer Rubrum* was calculated using a written program in a Microsoft Excel spreadsheet. Leaf and air temperature, wind speed, solar radiation, VPD, and measured transpiration were plotted for 24 hour periods as shown in Figure 2. Each day was chosen because it was either sunny or cloudy. For both cases, the trees were subjected to the highest transpiration stress during the mid-day when air and leaf temperature and radiation were all at the maximum levels and relative humidity was low.

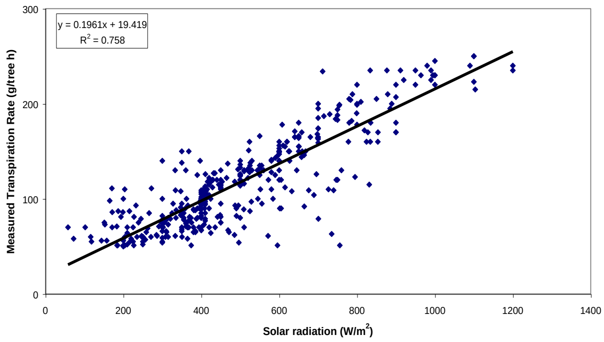


(a)

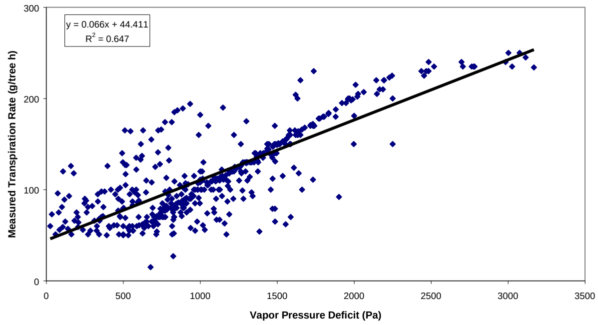


(b)

Figure 2. Air temperature, wind speed, measured transpiration and solar radiation, and vapor pressure deficit for Red Maple on a sunny day (8/14/97) (a) and a cloudy day (9/12/97) (b).



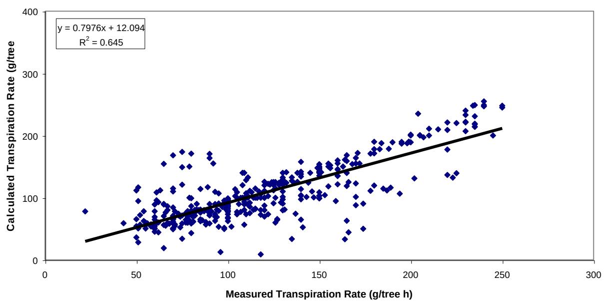
(a)



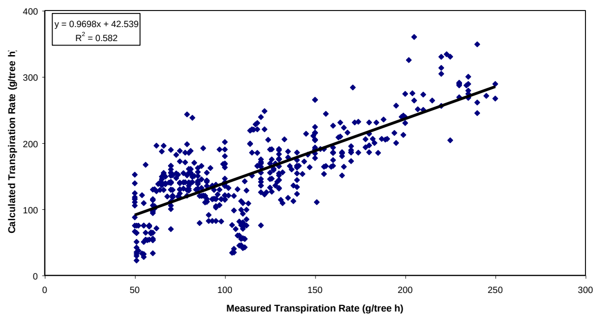
(b)

Figure 3. Correlation between solar radiation and measured ET rate (a) and VPD and measured ET (b) for two months of hourly data (excluding all night time data and/or data less than 50 g/tree h).

Figure 4 and 5 show that the correlation between calculated and measured hourly ET rates of Red Maple excluding all night time data for Fynn, Stanghellini and Penman ET models were 0.645, 0.644, 0.582 respectively.



(a)



(b)

Figure 4. Correlation between calculated and measured hourly ET rates of Red Maple based on deterministic ET models developed under greenhouse conditions; Fynn (a) and Stanghellini (b) (excluding all night time data and/or data less than 50 g/tree h).

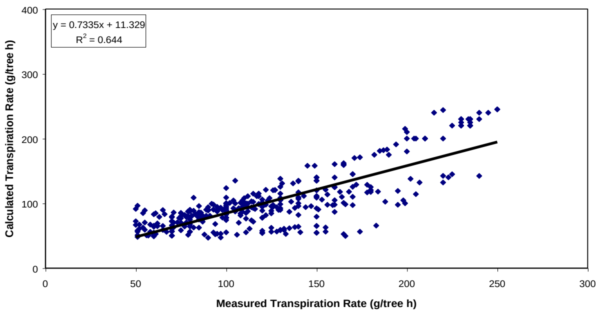


Figure 5. Correlation between calculated and measured hourly ET ates of Red Maple based on Penman method for two months (excluding all night time and/or data less than 50 g/tree h)

It was observed that the R^2 value of the VPD and solar radiation based stochastic ET model was better than the R^2 value of the deterministic ET models. The solar radiation based stochastic ET model was the best one in terms of the absolute R^2 value. 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 one since there was no resistance term in it.

One interesting observation interpreted from the data scatter points of the VPD based stochastic ET model (Figure 3b) was that there was almost a constant relationship between VPD and measured ET for small (500 Pa) and high VPD values (>2250 Pa). On the other hand, there was a positive trend between VPD and measured ET for the VPD values between 500 and 2250 Pa. This observation suggested that the solar radiation was the main driving force of the transpiration when VPD was relatively low and high.

Average measured ET and calculated ET for Fynn, Stanghellini and Penman were 840.12, 703.0, 674.3, and 1100.5 g/day respectively when excluding all night time data and/or data less than 50 g/tree h. This indicates that Fynn and Stanghellini ET models underestimated the measured ET 16.32% and 19.74% respectively. On the other hand, Penman ET model overestimated the measured ET 30.99%.

Figure 6 shows the average hourly transpiration rate for different ET methods along with measured ET during the experimental periods. It was observed that the Stanghellini and Fynn methods estimate the transpiration rate to be 16-20% lower than the measured ET during the noon periods whereas they estimate the transpiration rate higher than the measured ET during morning and late afternoon time periods. The Penman method estimated the ET rates higher than the measured ET for all times.

Figure 7 shows the air, leaf, medium temperature and tension variations for a clear (8/14/97) and a cloudy day (9/12/97). Average potting medium temperatures varied 1.5-2°C from the mean during the experimental period. The temperature of the potting medium at any time depended on the ratio of the energy absorbed to that being lost. A visual observation of the data indicated that medium temperature variations near the surface were high compared to the lower depth for the clear day and vise versa for the cloudy day. Submedium was cooler than surface medium layers because submedium was not subject to direct effects of solar radiation during the clear day. On clear days, temperatures near the medium surface layer did not reach its maximum until sometime after solar noon due to lag time. On cloudy days, medium temperature changes during the early morning and late nights were very close to each other due to the low incoming solar radiation. Overall, medium temperature changes on cloudy days were very low compared to clear days.

Another visual observation was that medium moisture had a significant influence on medium temperature. High medium moisture levels had small temperature changes due to its high specific heat. This supported the idea of [16] that moisture control in soil has more influence on soil temperature than any other soil management practice such as mulching.

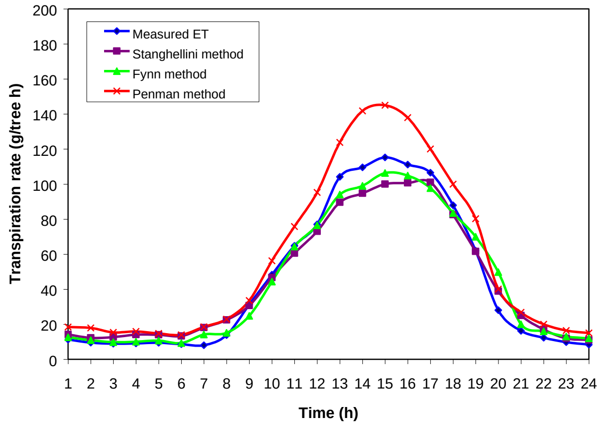


Figure 6. Average hourly transpiration rate for different ET methods for two month of experimental data.

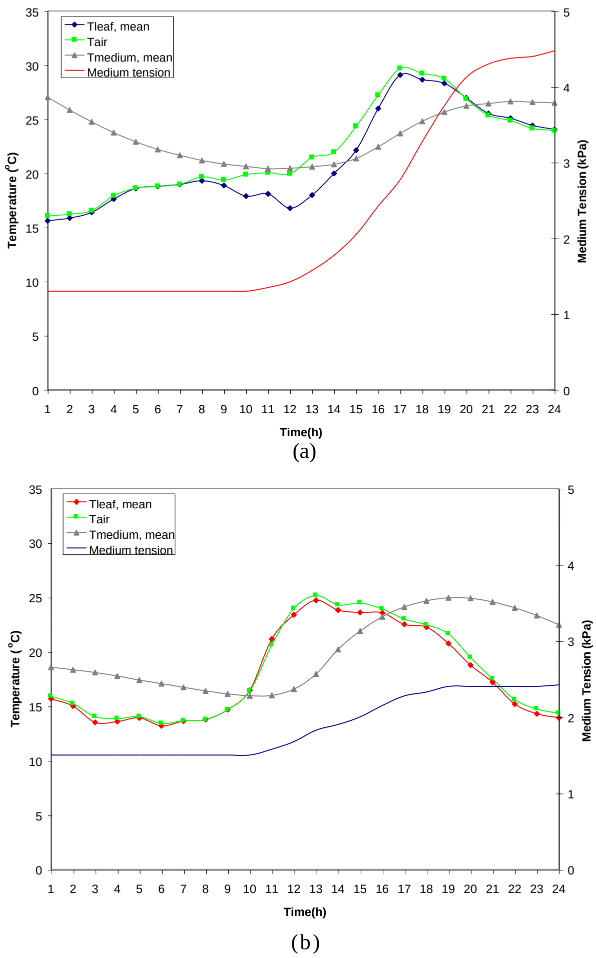


Figure 7. Air, leaf, medium temperature and medium tension variations for a clear (8/14/97), (a) and a cloudy day (9/12/97), (b).

CONCLUSIONS

Results of the linear regression analysis showed that there was high correlation between solar radiation, VPD and measured ET. A solar radiation or a VPD based stochastic ET model could be successfully used to predict ET rate of the plant. Comparing R^2 values of these two stochastic ET models, it was concluded that a solar radiation based stochastic ET model predicted ET better than the VPD based stochastic ET model.

The Stanghellini and Fynn ET models were similar to each other in terms of R^2 values and error in the prediction of ET. Even though Stanghellini and Fynn ET models were developed under greenhouse conditions, they predicted ET under field conditions better than Penman. The Penman model overestimated ET especially during the high transpiration periods while the Fynn and Stanghellini models underestimated ET during high transpiration periods.

Transpiration tended to be more proportional to VPD for cloudy days and more proportional to solar radiation for sunny days. The driving force for transpiration in late afternoon as the solar radiation was decreasing was VPD. The average daily evapotranspiration rate of the plant during the two months experimental period was approximately 1000 g per tree per day when all night time data was included.

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