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An Evapotranspiration Model for Nursery Plants Grown in a Lysimeter Under Field Conditions

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Abstract: A modified combination model that used ambient temperature, relative humidity, solar radiation, air velocity and leaf area index (LAI) as inputs was developed for nursery plants, and its prediction was compared to the measured ET of the plant. A nursery plant of red maple (*Acer rubrum*) grown in a lysimeter under field conditions was used to test it. This modified combination model was shown to accurately estimate the evapotranspiration (ET) of a potted red maple (R^2=0.79). The most significant driving parameters for ET were solar radiation level and vapor pressure deficit (VPD). An exponential relationship between stomatal resistance and solar radiation for red maple was established. This study showed that a combination ET model involves both environmental conditions and plant canopy characteristic is the best way to predict evatranspiration rate of the nursery plants.

Key Words: Evapotranspiration, *Acer rubrum*, solar radiation, Vapor pressure deficit, Stomata, Evapotranspiration model, Nursery production.

Tarla Koşullarında Lizimetrede Yetiştirilen Fidanlar için bir Evapotranspirasyon Modeli

Özet: Yaprak alan indeksi (LAI), rüzgar hızı, solar radyasyon, nisbi nem ve hava sıcaklığını girdi olarak kullanan yeniden düzenlenmiş bir kombinasyon ET modeli fidanlar için geliştirilmiş ve anılan modelin bitki su tüketimi tahmini, bitkinin gerçek su tüketimi ile karşılaştırılmıştır. Bu modeli test etmek için, tarla koşullarında lizimetrede yetiştirilen Kırmızı Akçaağaç *(Acer Rubrum)* fidanları kullanılmıştır. Yeniden düzenlemiş bu kombinasyon modelinin lizimetrede yetiştirilen Kırmızı Karaağaç bitkisinin su tüketimini doğru bir biçimde tahmin ettiği belirlenmiştir (R^2=0.79). Solar radyasyon ve havanın nem açığının ET' yi yönlendiren en önemli parametreler olduğu saptanmış, stoma direnci ile solar radyasyon arasında üslü bir ilişki olduğu ortaya konulmuştur. Bu çalışma, bitki su tüketimi hesaplamasında hem çevre koşulları hem de bitki örtüsü özelliklerini bir arada kullanan kombinasyon ET modelinin en doğru yaklaşım olduğunu göstermiştir.

Anahtar Sözcükler: Evapotranspirasyon, Kırmızı Akçaağaç, Solar radyasyon, Buhar basıncı acığı, Evapotranspirasyon modellemesi, Fidan üretimi.

Introduction

Evapotranspiration (ET) is the combined process of evaporation from soil and plant surfaces and transpiration from plants. Evapotranspiration requires two essential components: a source of energy and a vapor transport mechanism. Energy is needed to provide the latent heat of vaporization required to bring about a phase change from liquid to vapor. The vapor transport mechanism is necessary to continuously move the water vapor away from the surface and thus maintain a vapor pressure gradient between the evaporating surface and the surrounding air. Previous studies show that equations that combine both energy conservation (energy-balance equations) and aerodynamic principles (mass-transfer equations) predict ET most accurately (1).

Since ET is the primary process affecting irrigation requirements of plants, precise estimation of ET is very important in agriculture production. Early ET studies focused on the evaporative demand concept to establish the upper bounds of crop evaporation. With plants as a link between a soil water state and an evaporative demand state, the soil-plant interface and the crop canopy-atmosphere interface provided two boundary conditions for studying crop water use (1,2).

The combination equation to calculate crop ET under field conditions was first introduced by (3). The combination model was modified by introducing the crop-canopy resistance term (4). Later, this equation was modified by (5) for irrigation studies. Soil-to-canopy resistance was much lower than canopy-atmosphere resistance throughout a wide range of soil water potential, from -1 to –10 bars (2).

The soil-plant interface has been included in both macroscopic (6) and microscopic (7) approaches. The crop canopy-atmosphere interface has been studied from both single-leaf (8) and multi-layer crop canopy models (9,10). However, many researchers have used the macro-modeling approach, relying on the uniform properties assumption.

One important parameter for the combination model is stomatal resistance. Many researchers (2,10,11) have indicated that stomatal resistance depends primarily on solar radiation. The aim of this study was to establish a modified combination ET model using basic climatological data and plant characteristics for potted nursery plants. In addition, the relationship between stomatal resistance and solar radiation was investigated.

A Modified Combination ET Model

The first law of thermodynamics states that energy is neither created nor destroyed but is only transformed from one form to another. According to Monteith (4), if the first law of thermodynamics is applied to a plant canopy, the following equation is obtained:

$$Rn = LE + H + S \quad \text{[Eq.1]}$$

where Rn = net radiation at canopy surface ($W.m^{-2}$), LE = energy used by the ET process (latent heat flux) ($W.m^{-2}$), H = sensible heat energy transfer ($W.m^{-2}$) and S = heat energy storage ($W.m^{-2}$).

Eq. 1 shows the surface energy balance for a plant canopy, and is based on the physical principles of energy and matter conservation in the plant's environment. The latent heat flux is the major consumer of energy when water is available and solar radiation is the major supplier of energy. Plants can store energy generated by photosynthesis and changes in leaf temperature. In comparison with the other terms in Eq. 1, the value of S is negligible and often ignored. Therefore, the energy balance at the surface of a plant canopy can be defined by

$$Rn = LE + H \quad \text{[Eq. 2]}$$

Eq. 2 is a single-layer model, and thus assumes the structure of the canopy to have a single-layer. Multiple-layer models for the calculation of ET were not used due to their high degree of complexity. The major assumptions for a single-layer combination model are (a) that there is always sufficient readily available water in the soil, and (b) that transmissivity, absorption, reflectivity and temperature are uniform throughout the plant canopy (12).

Sensible energy transfer by convection at the leaf surface can be estimated by Ohm's law, according to which, the ratio between the potential difference and resistance gives the current. When which is applied to a leaf surface, the following equation is obtained based on (4):

$$H = \frac{(T_L - T_a)\ C_p\rho}{r_a} \quad \text{[Eq. 3]}$$

where T_a = ambient air temperature above the canopy (°C), T_L = average leaf temperature for the entire canopy (°C), C_p = specific heat capacity of dry air (volumetric heat capacity, $Jkg^{-1}\ °C^{-1}$), ρ = density of air (Kgm^{-3}), and r_a = aerodynamic resistance (sm^{-1}).

The same procedure used for Eq. 3 can be used to estimate the vapor transport function. Therefore, latent energy flux of water vapor at the leaf surface is defined as follows:

$$LE = \frac{[e_s\ (T_L) - e\ (T_a)]\ C_p\rho}{\gamma\ (r_s + r_a)} \quad \text{[Eq. 4]}$$

where e_s = saturated vapor pressure at leaf temperature (Pa), e = vapor pressure at air temperature (Pa), γ = psychometric constant (Pa $°C^{-1}$) and r_s = resistance to water vapor transfer from inside to outside the leaf, or stomal resistance ($s.m^{-1}$).

Since measurement of leaf temperature can be expensive and difficult, leaf temperature can be replaced in the equation with air temperature by using the psychometric curve (saturation vapor pressure vs. temperature) in Figure 1. The water vapor difference between the leaf surface and air can be approximated by linearization as follows:

$$e_s\ (T_L) - e\ (T_a) = \Delta\ (T_L - T_a) + VPD \quad \text{[Eq. 5]}$$

where Δ = slope of the saturation vapor pressure vs. temperature (Pa $°C^{-1}$), and VPD= vapor pressure deficit (Pa).

The vapor pressure deficit of air can be written as

$$VPD = e^*(T_a) - e\ (T_a) \quad \text{[Eq. 6]}$$

where $e^*(T_a)$ = saturation vapor pressure of air at ambient temperature (P_a), and $e(T_a)$ = actual vapor pressure of the air (Pa).

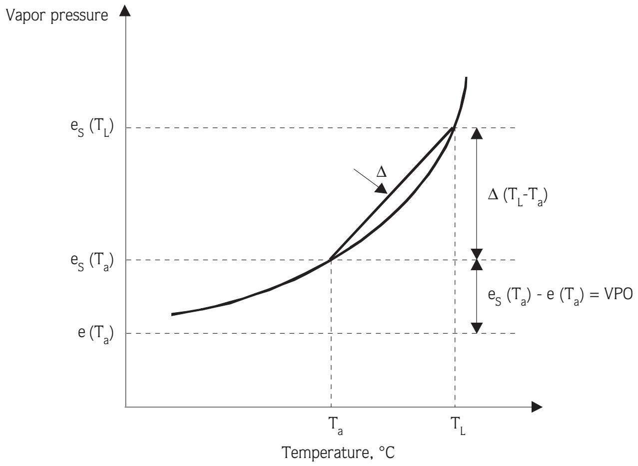

Figure 1. Psychometric curve modified from (13).

From Eqs. 2 and 3, the H and $(T_L - T_a)$ terms can be defined as

$$(T_L - T_a) = \frac{H.r_a}{C_p\,\rho} \qquad \text{[Eq. 7]}$$

$$H = Rn - LE \qquad \text{[Eq. 8]}$$

Substitution of Eqs. 7 and 8 in Eq. 5 yields

$$e_s(T_L) - e(T_a) = \Delta\,\frac{Hr_a}{C_p\rho} + VPD = \Delta\,\frac{(Rn - LE)\,r_a}{C_p\rho} + VPD \qquad \text{[Eq. 9]}$$

Substitution of Eq. 9 in Eq. 4, and then solving for LE yields

$$LE = \frac{\left[\frac{\Delta\ (R_n - LE)r_a}{C_p\,\rho} + VPD\right] C_p\,\rho}{\gamma\,(r_s + r_a)} \qquad \text{[Eq. 10]}$$

By mathematical manipulation, LE can be rewritten as

$$LE = \frac{\left[\frac{\Delta\ (R_n - LE)r_a\,C_p\rho}{C_p\,\rho} + C_p\,\rho\,.VPD\right]}{\gamma\,(r_s + r_a)} \qquad \text{[Eq. 11]}$$

Dividing each term to r_a in Eq. 11 yields the following equation:

$$LE = \frac{\Delta\ (R_n - LE) + C_p\,\rho.VPD.r_a^{-1}}{\gamma\left(1 + \frac{r_s}{r_a}\right)} \qquad \text{[Eq. 12]}$$

By mathematical manipulation of Eq. 12, Eq. 13 is obtained:

$$\Delta Rn + C_p\rho\ .VPD.r_a^{-1} = LE\left[\gamma\left(1 + \frac{r_s}{r_a}\right) + \Delta\right] \qquad \text{[Eq. 13]}$$

If Eq. 13 is solved for LE, the following equation is obtained:

$$LE = \frac{\Delta Rn + C_p\rho.VPD.r_a^{-1}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \qquad \text{[Eq. 14]}$$

Eq. 14 assumes that resistance of air to water vapor transfer is equal to the resistance of air to heat transfer, and thus assumes that the turbulent exchange capacity for heat and water vapor is similar. Eq. 14 is based on per unit area of plant canopy. In order to consider the whole plant, Eq. 14 should incorporate the leaf area index (LAI). Eq. 14 incorporates two major components of ET (heat transfer and vapor transfer), and LAI directly affects both components. Therefore, Eq. 14 should be multiplied by 2*LAI in order to consider both sides of the leaf. Thus, Eq. 14 becomes:

$$LE = 2LAI\,\frac{\left[\Delta Rn + C_p\rho.VPD.r_a^{-1}\right]}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)} \qquad \text{[Eq. 15]}$$

where r_c = canopy resistance ($s.m^{-1}$).

When Eq. 15 is divided by the term which expresses the latent heat of vaporization of water, the ET rate of the plant is obtained as follows:

$$LE = \left[2LAI\,\frac{\left[\Delta Rn + C_p\rho.VPD.r_a^{-1}\right]}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)}\right]\frac{1}{L_v} \qquad \text{[Eq.16]}$$

where ET = evapotranspiration rate ($kg\ m^{-2}\ s^{-1}$) and L_v = latent heat of vaporization of water (Jkg^{-1}).

Some ET models such as (2,9) do not include a wind speed variable. On the other hand, other ET models (3,4) include a wind parameter but no LAI variable. However, the advantages of this modified version of the combination model are that it includes both wind speed and LAI variables in one formula.

Aerodynamic and Canopy Resistance

Aerodynamic resistance (r_a) is used to indicate resistance to sensible-heat or water vapor, which are assumed to be equal. Estimation of the aerodynamic resistance of the vapor flux is often based on the wind speed in the boundary layer above the canopy, as well as on the displacement height and roughness length of the canopy.

In the electrical analog shown in Figure 2, ET was assumed to be process of a vapor current escaping from the leaf surface into the atmosphere. This current encounters two resistances in series: leaf stomatal resistance (r_s) and aerodynamic resistance (r_a).

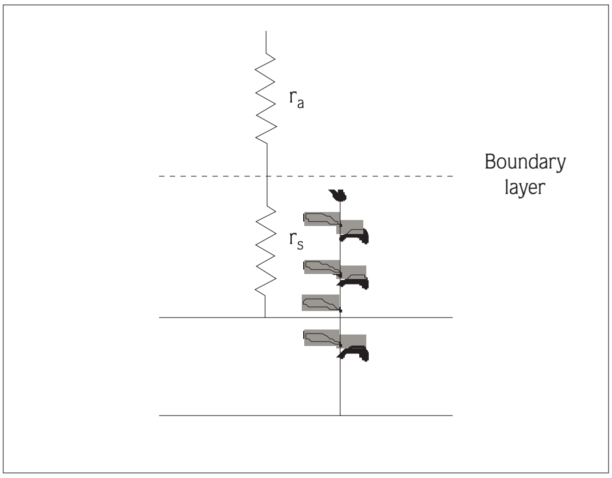

Figure 2. Electrical analogue of leaf stomatal and aerodynamic resistance.

According to Jensen et al. (14), aerodynamic resistance can be calculated as

$$r_a = \frac{\ln\left(\frac{Z_a - d}{Z_{om}}\right) \ln\left(\frac{Z_t - d}{0.13 Z_{om}}\right)}{K^2 U_a} \qquad \text{[Eq. 17]}$$

where Z_a = height of the anemometer (wind) measurement above ground (m), Z_t = height of temperature and relative humidity measurements above the ground (m), d = displacement height of vegetation (m), Z_{om} = roughness height of vegetation (m), k= Von Karman's constant for turbulent diffusion (k=0.41) and U_a= wind speed at the anemometer height ($s.m^{-1}$).

Displacement and roughness height are assumed to be fixed proportions of the canopy height (14,15). The displacement height and roughness height are functions of the surface roughness elements, but also depend on the density and arrangement of the roughness element and possibly wind speed (15,16). These were simplified by (4) as shown in Eqs. 18 and 19. The zero-plane displacement height is assumed to be fixed at a constant proportion of crop height.

$$d=0.67\ h_c \qquad \text{[Eq. 18]}$$

where h_c= canopy height (m).

Roughness heights are assumed to be constant proportions of vegetation height.

$$Z_{om} = 0.123\ h_c \qquad \text{[Eq. 19]}$$

Plant resistance basically represents bulk stomatal resistance and therefore can be estimated from measurements of individual leaf resistance in connection with LAI (13,15). Canopy resistance can be calculated as a function of individual leaf stomatal resistance and LAI by assuming that all leaves act in parallel:

$$r_c = r_s / 0.5\ \text{LAI} \qquad \text{[Eq. 20]}$$

Overall, the significance of this modified ET model, Eq. 16, is that it includes an important plant characteristic for transpiration, LAI, in the model, whereas some models (3,4) do not include the LAI variable.

The aerodynamic resistance was determined by measuring air speed over the plant leaves with Eq. 17. Since ET was measured by lysimeter, canopy resistance was determined by Eq. 16. By Eq. 20, stomatal resistance, rs, was determined.

Experimental Procedure and Measurements

In order to verify the modified combination equation explained above, an experiment was conducted under the field conditions at the Ohio Agricultural Research Development Center (OARDC), Wooster, Ohio, USA (41° 48 N' latitude), in August and September 1997. A gravel bed which was 25 m wide by 50 m long was formed for this experiment. The bed was constructed by laying a weed mat over a soil surface which was graded to a 0.2% slope with drain tile placed 0.5 m below the surface. Clean, graded, No. 57 limestone gravel (2 cm in diameter) was uniformly distributed on the top of the weed mat approximately 12 cm deep to complete construction of the bed. The nursery plant used was red maple *(acer rubrum)* potted in 26.5 L containers, and spaced on a 2 ¥ 2 m grid in the experiment area. Only one potted plant was on the lysimeter for measurements, and the others were on the gravel bed.

There were eighty-four potted *Acer rubrum* on the gravel bed around the lysimeter, which was placed in the middle of the experimental area. Since there was only one lysimeter, measurements were taken from only one plant on the lysimeter. In order to measure ET, a Sartorius F330S automatic weighing scale with an accuracy of ±1 g was placed beneath one of the tree containers. The lysimeter was located in the middle of the nursery growing area to represent the environment in the best way. The lysimeter was portable and sensitive. The lysimeter readings were recorded in print and on cassette with a Kaye Digistrip III datalogger.

The height and diameter of the container were 30 cm and 35 cm respectively, and the depth of the potting medium in the container was 20 cm. The potting medium used in the experiment, Metro Mix 510 (The Scotts Company, Marysville, OH), was common in the nursery industry and recommended for its good physical and chemical characteristics. A slow release fertilizer (Osmocote, 8-9 months with an N-P-K ratio of 18-6-12) was used to fertilize the plants.

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 a computer control system (Q-COM Inc., Irvine, CA) and continuously stored in GEM3V2 software at 15 minute intervals. Rainfall was measured manually using rain gages located at three different places in the experimental area.

A porous cup tensiometer with an electronic pressure transducer at the top was used to sense the medium tension. The tensiometer sensor consisted of a ceramic cup fastened to a transparent tube with an airtight seal. The tube was filled with water until there was small air column remaining at the top of the tube. The pressure transducer measured the vacuum in the air column and translated this vacuum pressure into an electrical signal. Then, this electrical signal was sent to a Q-COM computer with GEM3V2 software, which was used to sense and monitor the medium tension. GEM3V2 software requires a sampling tension interval and a numerical value for medium tension as inputs. In this experiment, potting media tension was allowed to increase to a maximum of 21 kPa to avoid plant stress based on (1), and the sampling interval for medium tension was 15 minutes.

The leaf temperature was measured from the upper, middle and bottom parts of the plant and averaged. The temperature of each leaf was measured using type T thermocouples of 0.127 mm in size inserted into the central veins from the underside of the leaf. The datalogger recorded leaf temperature readings at 15-minute intervals.

The leaf area index (LAI) was an input parameter for the deterministic ET model and was defined as the ratio of the total leaf area of a plant to the projected horizontal ground area of the plant canopy. In order to find LAI, the procedure mentioned by (12) was applied. During the experiment, a total of 10 leaves were removed from different parts of the plant in the lysimeter. An electronic leaf areameter was used to measure the area of each sample leaf, which was then averaged. Later, the number of leaves per plant was counted as a basis for determining the total leaf area. The horizontally projected ground area of the plant canopy was calculated assuming a rectangular shape since the shape of the canopy on the ground appeared to be mostly rectangular. LAI was found to be1.58.

Results and Discussion

Figures 3 and 4 show 24-h examples of evapotranspiration, solar radiation and VPD measured above the canopy for sunny and cloudy days respectively. In both cases, the plants were subjected to the highest transpiration stress during midday because air and leaf temperature and radiation were all at the maximum levels.

The average difference between leaf temperature and air temperature was 2-2.5°C. This temperature difference was due to evaporative cooling during high transpiration rates for midday conditions. Leaf temperature variations among bottom, top and middle levels of the canopy were about 5-6°C.

It was concluded that solar radiation was an independent variable actuating changes in stomatal resistance (2,10). An attempt was made to investigate factors such as leaf temperature that have been shown in other studies to affect stomatal resistance to

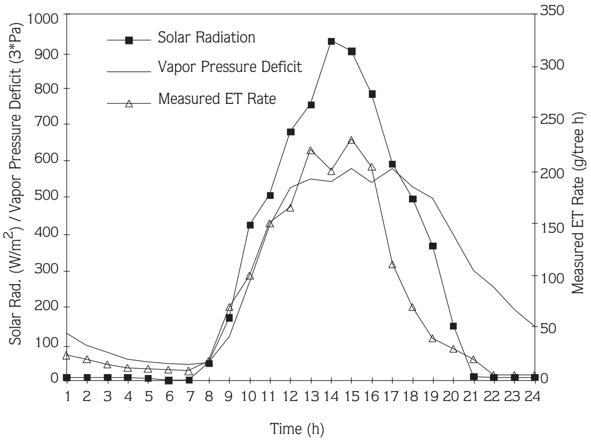

Figure 3. The effect of vapor pressure deficit and solar radiation on the ET rate of Red Maple on a sunny day (9/12/97).

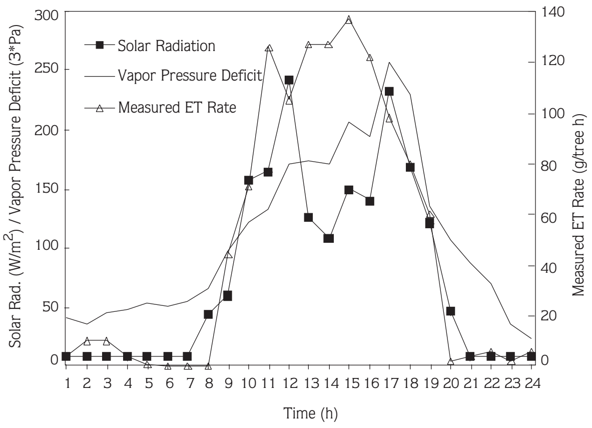

Figure 4. The effect of vapor pressure deficit and solar radiation on the ET rate of Red Maple on a cloudy day (8/19/97).

transpiration, but all changes in transpiration occurred simultaneously with exposure to sunlight. To observe the effects of solar radiation on stomatal resistance, a simple linear regression analysis was done. This relationship was derived (R^2=0.76) and is shown in Eq. 21.

$$r_s = 108.5+660\, e^{(-0.009\alpha)} \qquad \text{[Eq. 21]}$$

where α is the total shortwave solar radiation incident upon the canopy. The total shortwave solar radiation incident upon the canopy was obtained from the automatic recording weather station with a pyranometer located in the nursery growing area.

The correlation between ET and VPD, and that between ET and solar radiation were examined independently. In the morning, VPD and solar radiation are very low. However, when the sun rises, VPD and solar radiation increase, so the transpiration rate reaches its peak during midday. The modified combination equation, Eq. 16, accurately predicted the water requirements of the potted red maple, as shown in Figure 5.

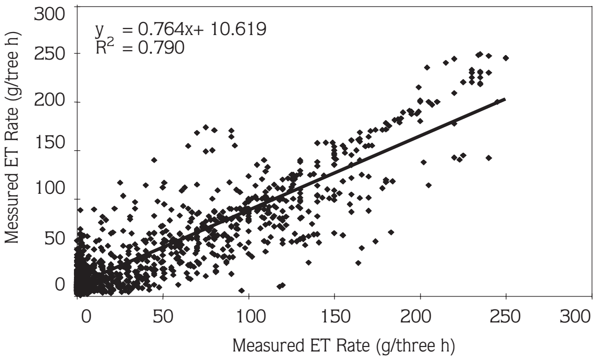

Figure 5. Correlation between predicted and measured hourly ET rates of Red Maple based on modified combination model.

The driving force for transpiration in the late afternoon and early morning was VPD. The transpiration tended to be more proportional to solar radiation on sunny days. However, transpiration tended to be more proportional to VPD on cloudy days. The results of linear regression analysis showed that there was a high correlation between solar radiation measured ET, as shown in Figure 6 (R^2=0.875), and VPD measured ET, as shown in Figure 7 with an R^2 of 0.684.

The daily transpiration rate of red maple was found to range from a minimum of 850 g tree^{-1} day^{-1} to a maximum of 1789 g tree^{-1} day^{-1} for sunny days. However, for cloudy days, it was found to range from a minimum of 450 g tree^{-1} day^{-1} to a maximum of 855 g tree^{-1} day^{-1}.

The most significant variables in the modified combination ET model were solar radiation and VPD. Solar radiation was also the main factor controlling stomatal resistance. Stomatal resistance was very high during the hours of darkness. On the other hand, the stomatal resistance decreased exponentially as the solar radiation increased.

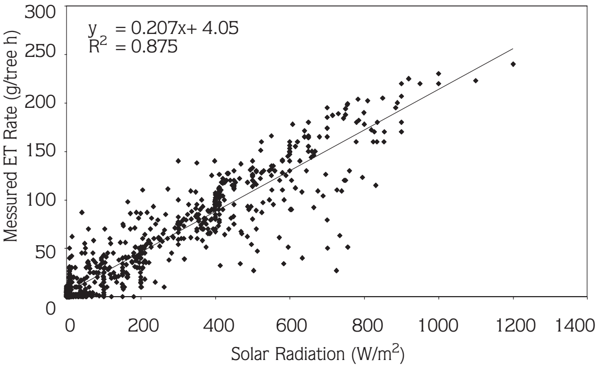

Figure 6. Correlation between solar radiation and measured ET rate of Red Maple.

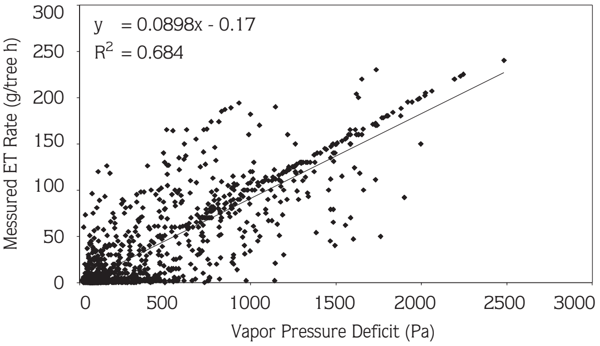

Figure 7. Correlation between VPD and measured ET rate of Red Maple.

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