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# Estimation of short-term actual crop evapotranspiration

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## ABSTRACT

A method is presented for estimating the hourly actual evapotranspiration (ET) from short natural vegetation or agricultural crops. The method consists of equating the ET flux equations based on the generalized Penman-Monteith (GPM) combination method and a humidity gradient (HG) method. By equating the GPM and HG expressions, a single unknown parameter, either the bulk surface resistance ($r_s$) or aerodynamic resistance ($r_a$), can be determined. In the procedure, the value of the resistance factor is adjusted until the daily ET time series curves from the two methods approximately coincide. An overview of the technical approach and the results of a comparison between the new method and an eddy covariance system at the University of Florida at Gainesville are provided. To illustrate the utility of the method an example is presented in which the average daily ET was determined for a growing season of common bean (*Phaseolus vulgaris* L.) at Juana Díaz, Puerto Rico. In this example the surface resistance was measured (i.e., stomatal resistance and leaf area) and estimated using the proposed method. A third method was also evaluated in which the surface resistance was estimated using the equation of Ortega-Farias and Fuentes (1999). All three methods were in close agreement.

**Key words:** Evapotranspiration, Penman-Monteith, Humidity gradient, Bowen ratio, Eddy covariance, Weighing lysimeter, Surface resistance, Aerodynamic resistance

## INTRODUCTION

Accurate estimates of actual evapotranspiration (ET) are costly to obtain. An inexpensive alternative is to estimate actual evapotranspiration by multiplying a potential or reference evapotranspiration by a crop coefficient ($K_c$) (Jensen et al., 1990). Although crop coefficients derived in other parts of the world can be used to provide approximate estimates of evapotranspiration, the crop coefficient in fact depends upon the specific crop variety and other local conditions (Harmsen, 2003).

Current methods for estimating actual evapotranspiration include weighing lysimeter, eddy covariance, and Bowen-ratio methods. Each of these methods has certain limitations. A method is described in this paper which provides an estimate of the actual

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ET from short natural vegetation or agricultural crops and is less expensive than the other methods mentioned above.

The objectives of this study were

- To describe a relatively inexpensive method for estimating actual evapotranspiration.
- Present preliminary validation results for the method.
- Present application example results from a field study conducted in Juana Díaz, Puerto Rico.

## METHODS

**Data Analysis.** The method used in this study consisted of equating the ET flux equations based on the generalized Penman-Monteith (GPM) combination method (Allen et al., 1998) with a humidity gradient (HG) method (Monteith and Unsworth, 1990). In the procedure, the value of one of the resistance factors (either the aerodynamic resistance, $r_a$, or the bulk surface resistance, $r_s$) is adjusted iteratively in the two equations until their ET time series curves approximately coincide. A similar approach was used by Alves et al. (1998) in which an independent estimate of ET was derived from the Bowen ratio method, $r_a$ was obtained from a theoretical equation, and $r_s$ was obtained by inversion of the Penman-Monteith equation.

The GPM combination equation is given as follows (Allen et al., 1998):

$$ET = \frac{\Delta \cdot (R_n - G) + \rho_a \cdot c_p \cdot \frac{(e_s - e_a)}{r_a}}{\lambda \cdot \left[\Delta + \gamma \cdot \left(1 + \frac{r_s}{r_a}\right)\right]} \qquad \text{(equ. 1)}$$

where $\Delta$ is slope of the vapor pressure curve, $R_n$ is net radiation, G is soil heat flux density, $\rho_a$ is air density, $c_p$ is specific heat of air, $\gamma$ is psychrometric constant, T is air temperature at 2 m height, $u_2$ is wind speed at 2 m height, $e_s$ is the saturated vapor pressure and $e_a$ is the actual vapor pressure, $r_a$ is the aerodynamic resistance and $r_s$ is bulk surface resistance.

The value of the aerodynamic resistance can be estimated with a theoretical equation, such as equation 2 below (Allen et al., 1998):

$$r_a = \frac{\ln\left[\frac{(z_m - d)}{z_{om}}\right] \cdot \ln\left[\frac{(z_h - d)}{z_{oh}}\right]}{k^2 \cdot u_2} = \frac{\xi}{u_2} \qquad \text{(equ. 2)}$$

where $z_m$ is height of wind measurement, $z_h$ is height of humidity measurement, d is zero plane displacement height equal to 0.67 h, h is crop height, $z_{om}$ is roughness length governing momentum transfer equal to 0.123 h, $z_{oh}$ is roughness length governing transfer of heat and vapor equal to 0.1 $z_{om}$, and k is von Karman's constant (0.41). Allen et al. (1998) reported that equation 2 and the associated estimates of d, $z_{om}$ and $z_{oh}$ are applicable for a wide range of crops. Equation 2 is restricted to neutral stability conditions, i.e., where temperature, atmospheric pressure, and wind velocity distribution follow nearly adiabatic conditions (no heat exchange). A study of surface and aerodynamic resistance performed by Kjelgaard and Stockle (2001) determined that equation 2 will produce reliable estimates of $r_a$ for small crops.

In this study the functional form of the gradient flux equation was used:

$$ET = \left(\frac{\rho_a \cdot c_p}{\gamma \cdot \rho_w}\right) \cdot \frac{(\rho_{vL} - \rho_{vH})}{(r_a + r_s)} \qquad \text{(equ. 3)}$$

where $\rho_w$ is the density of water, $\rho_v$ is the water vapor density of the air, and L and H are vertical positions above the ground. All other variables were defined previously.

In this study L and H were 0.3 m and 2 m above the ground, respectively. Equation 3 is essentially identical to the latent heat flux equation presented by Monteith and Unsworth (1990, equation 15.9) except that their formulation was based on the vapor pressure deficit (VPD). The VPD is the saturated air vapor pressure minus the actual vapor pressure. In our formulation we rely only on actual vapor pressures. It is important to note that the resistance factors in equation 3 are identical to those used in equation 1.

**Field Data Analysis.** Climatological data were saved on a Campbell Scientific (CS) CRX10 data logger every 10 seconds. Net radiation was measured using a NR Lite Net Radiometer. Wind speed was measured 3 m above the ground using a MET One 034B wind speed and direction sensor. The wind speed at 3 m was adjusted to the 2 m height using the logarithmic relation presented by Allen et al. (1998). Soil water content was measured using a CS616 Water Content Reflectometer. Soil temperature was measured using two TCAV Averaging Soil Temperature probes, and the soil heat flux at 8 cm below the surface was measured using a HFT3 Soil Heat Flux Plate.

An automated elevator device was developed for moving the Temp/RH sensor between the two vertical positions. The device consisted of a plastic (PVC) frame with a 12 volt DC motor (1/30 hp) mounted on the base of the frame. One end of a 2-m long chain was attached to a shaft on the motor and the other end to a sprocket at the top of the frame. Waterproof limit switches were located at the top and bottom of the frame to limit the range of vertical movement.

For automating the elevator device a programmable logic controller (PLC) was used which is composed of "n" inputs and "n" relay outputs. To program the device, a ladder logic was used, which is a chronological arrangement of tasks to be accomplished in the automation process. The Temp/RH sensor was connected to the elevator device, which measured RH and temperature in the up position for two minutes then changed to the down position where measurements were taken for two minutes, and the process continued indefinitely until the experiment was ended. When the elevator moves to the up position it activates the limit switch which sends an input signal to the PLC. That input tells the program to stop and remain in that position for two minutes. At the same time it activates an output which sends a 5 volt signal to the control port C2 in the CR10X data logger in which a small subroutine is executed. This subroutine assigns a "1" in the results matrix which indicates that the temperature and relative humidity correspond to the up position. At the end of the two minutes period the elevator moves to the down position and repeats the same process, but in this case sending a 5 volts signal to the data logger in the control port C4, which then assigns a "2" in the results matrix.

To facilitate post-processing of the large data sets generated from the weather station a computer program (spreadsheet macro) was developed. The program separates the data from the "up" and "down" positions and calculates the actual evapotranspiration by equation 1 and equation 3.

The new method was preliminarily verified by comparing ET results for April 5th and 6th, 2005, with an eddy covariance system at the University of Florida (UF) Plant Science Research and Education Unit (PSREU) near Citra, Florida. The eddy covariance system was located in the center of a 23 hectare bahia grass field and the shortest distance from the station to the edge of the field was 230 m.

## RESULTS

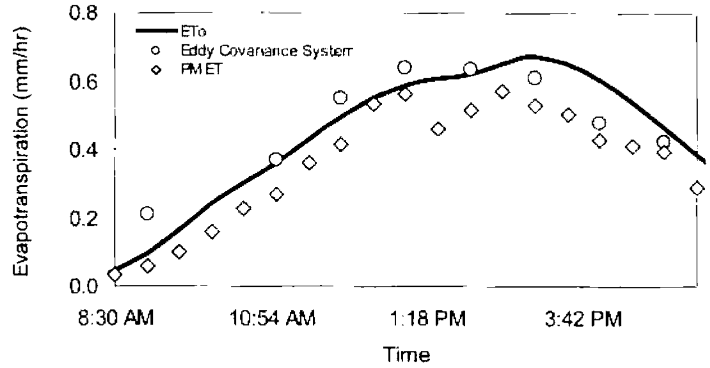
For convenience, the equipment used in this study involving a standard weather station and an elevator device for obtaining the temperature and humidity gradients, will be referred to as the ET station. On April 5th and 6th, 2005, the ET station was set up next to an eddy covariance system. The goal of the experiment was to compare the ET estimates from the ET station, eddy covariance system, and three weighing lysimeters. Unfortunately, the grass on the weighing lysimeters was damaged from a recent herbicide application, and consequently the data from the lysimeters could not be used. Therefore, validation of the ET station was limited to comparisons with the eddy covariance system.

During the two day experiment the weather was excellent with relatively few clouds. On both days, except for early morning, the relative humidity was in the range of 40 to 60% and high temperatures were around 28 °C. The field was covered with bahia grass *(Paspalum notatum)*, having average height of 15 cm and receiving irrigation regularly via a linear-move irrigation system. On the night of April 4th, just before the beginning of the experiment, the field received 15 mm of irrigation.

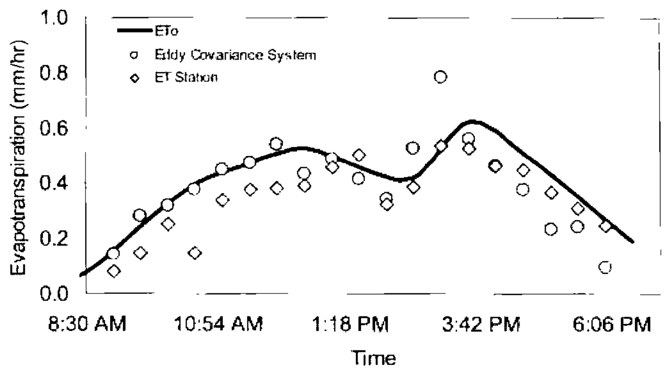
To estimate the ET using data from the ET station the following steps were used:

1. The data were read into the spreadsheet macro which, among other things, separated the "up" and "down" humidity and temperature data, and calculated actual vapor pressures.
2. The approach used in this case was to estimate the aerodynamic resistance ($r_a$) using equation 2 based on a 15 cm plant height, which yielded a value of $\zeta = 191$.
3. The ET estimates from equations 1 and 3 were plotted together on the same graph, and the value of $r_s$ was adjusted until the two datasets approximately coincided. The two datasets were considered to be in agreement when their total daily ET was within 0.01 mm of each other.

Figure 1 shows the short-term estimates of ET on April 5th (a) and April 6th (b), 2005 at the PSREU near Citra, Florida. The total daily ET for both methods was 3.66 mm, and the final value of $r_s$ was equal to 160 $sm^{-1}$. The Penman-Monteith reference evapotranspiration is also shown in the figure.




(a)




(b)

Figure 1. Evapotranspiration estimated using the eddy covariance system and ET station on (a) April 5th, 2005 and (b) April 6th, 2005 at the University of Florida Plant Science Research and Education Center near Citra, Fla. Reference evapotranspiration is also presented.

Table 1 lists the estimated daily ET data from the eddy covariance system and the ET station for April 5th and 6th, 2005. The ET estimates by the two methods are in reasonably good agreement. The daily average crop coefficients ($K_c$) in Table 1 are in the range reported for mature turf grass (cool season 0.95, warm season 0.85) (Allen et al., 1998). The table also includes the parameters $\zeta$ and $r_s$. Values of $\zeta$ and $r_s$ for the reference evapotranspiration were obtained from Allen et al. (1998) for the imaginary reference grass ($\zeta$ = 208 and $r_s$ = 70 s $m^{-1}$).

Table 1. ET as determined from the eddy covariance system and the ET station. The Penman-Monteith reference evapotranspiration, daily average crop coefficients ($K_c$), and values of $\zeta$, and $r_a$ are also included.

| Date | Method | Daily ET (mm) | $K_c$ | $\zeta$ | $r_s$ (s/m) |
|---|---|---|---|---|---|
| 4/5/2005 | PM - $ET_o$ | 4.37 | | 208 | 70 |
| | Eddy Covariance | 3.92 | 0.90 | | |
| | ET station | 4.11 | 0.94 | 191 | 157 |
| 4/6/2005 | PM - $ET_o$ | 4.06 | | 208 | 70 |
| | Eddy Covariance | 3.78 | 0.93 | | |
| | ET station | 3.66 | 0.90 | 191 | 160 |

**Application Study.** A drought tolerance study of common bean (*Phaseolus vulgaris* L., genotype Morales) was conducted between January and April 2006 at the University of Puerto Rico Fortuna Agricultural Experiment Station near Juana Díaz, Puerto Rico. Four ET stations were installed in adjacent non-stressed plots. Reference evapotranspiration was obtained from an adjacent well-watered field using a WatchDog (Spectrum Technology, Inc.) weather station.

Table 2 compares the average daily ET obtained by the method presented in this paper (No. 1), and use of equation 1 only with $r_s$ measured with a Delta-T AP4 porometer (No. 2).

Table 2. Comparison of ET.

| No. | Method | ET mm $day^{-1}$ | S.D. | S.E. | Min | Max |
|---|---|---|---|---|---|---|
| 1 | $r_s$ method presented in this paper | 4.15a | 1.41 | 0.34 | 1.80 | 8.00 |
| 2 | $r_s$ measured | 3.81a | 1.08 | 0.26 | 2.05 | 5.70 |
| 3 | $r_s$ calculated | 4.34a | 1.20 | 0.29 | 2.00 | 6.70 |

Estimates for beans grown at the UPR Fortuna Agricultural Experiment Station, Juana Díaz, P.R.

S.D is standard deviation. S.E is the standard error. n=17. Different letters denote statistical differences ($P<0.05$) LSD.

ET was also obtained using equation 1 and 2, and $r_s$ derived by the method of Ortega-Farías and Fuentes (1999) as given below (Table 2, No. 3):

$$r_s = \frac{\rho_a \cdot C_p \cdot VPD}{\Delta \cdot (R_n - G)} \cdot \frac{\theta_{FC} - \theta_{WP}}{\theta - \theta_{WP}} \qquad \text{(equ. 4)}$$

where θ is soil volumetric moisture content, FC is field capacity, WP is wilting point, and all other variables were defined previously.

There was no significant difference between the three methods used to estimate ET. Of the three methods, the method involving the use of equation 4 is the easiest to implement and the data necessary can be obtained using a standard weather station along with soil moisture data. The method has the disadvantage that it does not provide the vertical humidity and temperature gradients, as is obtained using the ET station and therefore the Bowen Ratio cannot be calculated.

A disadvantage of all the methods discussed in this paper is that they all require a relatively flat topography, no regional advection and sufficient upwind fetches.

## CONCLUSION

This paper described a method for estimating actual ET that is equally accurate and is less expensive than the eddy covariance method. The method used in this study consisted of equating the ET flux equations based on the generalized Penman-Monteith combination method with a humidity gradient method. In the procedure, the value of one of the resistance factors (either the aerodynamic resistance, $r_a$, or the bulk surface resistance, $r_s$) is adjusted iteratively in the two equations until their ET time series curves approximately coincide.

The method was validated (preliminarily) by comparison with an eddy covariance station located at the University of Florida Plant Science Research and Education Center near Citra, FL on April 5$^{th}$ and 6$^{th}$, 2005. ET estimates from a field experiment near Juana Diaz, PR, with common beans indicated that the method gave comparable results with estimates using the measured surface resistance.

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