Estimation of Actual Evapotranspiration Using Measured and Calculated Values of Bulk Surface Resistance

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ABSTRACT

The Penman-Monteith model (PM) is a useful "one-step" method for evapotranspiration (ET) estimation, if surface resistance (r_s-ms^{-1}) estimates can be derived. This study has as its objective to evaluate different methods of r_s estimation and the accuracy of the resulting ET estimates in common bean (*P. vulgaris* L.). The experiment was conducted at the Fortuna Agricultural Experiment Station at Juana Diaz, PR. Four automated weather stations were placed in plots planted with two genotypes of common bean (*Phaseolus vulgaris* L.). Net radiation, soil heat flux, soil temperature, soil moisture, air temperature, relative humidity, wind speed and direction were recorded at ten second intervals. Each weather station had an elevator system that moved the air temperature and relative humidity sensor between two vertical positions over the crop canopy every two minutes during a complete day. The r_s was derived by stomatal resistance (r_L) and leaf area index (LAI) measurements (PM-1), and by direct micrometeorological variables as follows: inverse of the general PM-model (PM-2), as a function of the soil moisture (PM-3), and as a latent heat flux-λE (PM-4 and ET-Station). The results indicate that PM-1 under-estimated r_s at low LAI, and that r_s and r_L are influenced inversely by the aerodynamic resistance (r_a), which affected the precision of the PM-2 and ET station estimation especially under windy and dry conditions, but not the PM-3 and PM-4 methods.

INTRODUCTION

An accurate estimation of evapotranspiration is necessary for appropriate agricultural water management. The most precise method for estimating ET is the mass balance method using weighing lysimeters, but its principal disadvantages are cost and immobility. Evapotranspiration may also be estimated based on micrometeorological methods, which have been used with good precision in many countries and with different vegetative covers. The generalized Penman-Monteith model (PM) for estimating ET has been recommended by the United Nations Food and Agriculture Organization (FAO) as the sole meteorological method that should be used in the world. However, one of its limitations is the inability to obtain an estimate of the surface resistance (r_s). Surface resistance is a required input for the method, however tables with effective r_s values for different crops are lacking, such as are available for the evapotranspiration crop coefficient (Shuttleworth, 2006).

The Drainage and Irrigation Paper-FAO56 (Allen et al. 1998), recommends the Szeicz and Long (1969) method for calculation of r_s, in which an average of r_L for different positions within the crop canopy, weighted by LAI or $LAI_{effective}$ is used. This method seems to give good results only in very rough surfaces, like forest and partial cover crops with a dry soil (Monteith, 1981). Alves et al. (1998) concluded that r_s of dense crops cannot be obtained by simply averaging stomatal resistance (r_L) because the vapor pressure deficit (VPD) which is the "driving force" is not constant within the canopy. Alves and Pereira (2000) have stated "The PM model can be used to predict ET if accurate methodologies are available for determining the r_s that take into account the energy partitioning".

In addition to the lack of r_s values for crops, questions have been raised relative to the appropriateness of using the PM model for partial or sparse canopies because the source/sink fluxes may be distributed in a nonuniform manner throughout the field (Kjelgaard et al. 1994; Farahami and Bausch, 1995; Ortega-Farias et al. 2006). Adequate parameterization of the surface resistance makes the PM model a good tool for ET estimation (i.e., Rana et al. 1997; Alves and Pereira, 2000; Ortega-Farias et al. 2004).

There is a need to evaluate existing methods to determine r_s under variable canopies and soil moisture conditions in common bean, and to apply it to "one step" ET calculation. Therefore, in this work, we compare ET estimates using the "one-step" or generalized PM model, using r_s derived from measured r_L and LAI, and derived from micrometerological and soil moisture data.

Theoretical background. The evapotranspiration from a crop canopy, as expressed by the generalized Penman-Monteith (PM) equation, has been presented by Allen et al. (1998) in the following equation:

$$\lambda E = \frac{\Delta(Rn - G) + \rho_a C_p \dfrac{VPD}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_a}\right)} \qquad (1)$$

where λE is Latent heat flux [Wm^{-2}], Rn is net radiation [Wm^{-2}], G is soil heat flux [Wm^{-2}], VPD is vapor pressure deficit [kPa], Δ is the slope of the saturation vapor pressure curve [$kPa\ ^{\circ}C^{-1}$] at air temperature, ρ_a is the density of air [Kgm^{-3}], C_p is the specific heat of air [$J\ Kg^{-1}\ ^{\circ}C^{-1}$], γ is the psychometric constant [$kPa\ ^{\circ}C^{-1}$], *VPD* is the vapor pressure deficit, r_a is the aerodynamic resistance [$s\ m^{-1}$], r_s is the surface resistance to vapor transport [$s\ m^{-1}$]. Crop evapotranspiration was estimated by dividing λE by λ. Equation 1 is referred to as the "one step" method because it does not rely on the use of a crop coefficient.

Aerodynamic resistance describes the resistance of heat and water vapor transport from the evaporating surface into the air above the canopy and was estimated with equation 2 (Allen et al. 1998, and Alves et al. 1998).

$$r_a = \frac{Ln\left[\frac{(Z_m - d)}{Z_{om}}\right] Ln\left[\frac{(Z_h - d)}{Z_{oh}}\right]}{k^2 u_z} \tag{2}$$

where Z_m is the height of wind measurements [m], z_h is the height of humidity measurements [m], d is the zero displacement height [m] is 2/3h, Z_{om} is the roughness length governing momentum transfer of heat and vapor [m] is 0.123h, Z_{oh} is the roughness length governing transfer of heat and vapor [m] is $0.1Z_{om}$, k is the von Karman`s constant [0.41] and u_z is the wind speed at height z.

The bulk surface resistance describes the resistance of vapor flow through the transpiring crop and evaporation from the soil surface. The surface resistance involves plant parameters like stomatal resistance and leaf area index. Szeicz and Long (1969) proposed the use of equation 3 to estimate surface resistance, which can be used when the evaporation from the soil is negligible, when the surface resistance of a crop may be very close to the compound resistance of all its leaves in parallel. In a fully developed canopy, the lower leaves may not be illuminated well enough to open their stomates, therefore, the effective LAI contributing to transpiration is less than the total leaf area, and for this reason the active LAI_{active} = LAI x 0.5 can be used (Allen et al. 1998):

$$r_s = \frac{r_L}{LAIactive} \tag{3}$$

where r_s is bulk surface resistance (s m^{-1}), LAI_{active} is 0.5 times the leaf area index (m^2 leaf by m^2 the soil), and r_L is stomatal resistance equal to the average resistance of the individual, well-illuminated leaf (s m^{-1}).

Harmsen et al. (2006) developed a method to estimated resistance factors when one of them (i.e., r_s or r_a) is not available or measured. In this study, this method is referred to as the ET-Station method, and relies on a functional form of the gradient flux equation (4) in combination with generalized PM equation (1):

$$ET = \left[\frac{\rho_a . c_p}{\gamma . \rho_w}\right] . \frac{[\rho_{vL} - \rho_{vH}]}{r_a + r_s} \tag{4}$$

where ρ_w is the density of water, ρ_v is the water vapor density of the air, and L (down) and H (up) are vertical positions above the ground. All other variables were defined previously. In this study, L and H were 0.2 m and 2 m above the ground. This method uses only the actual vapor pressures (converted to vapor densities, equation 4), unlike the use of the VPD in the PM method. It is important to note that the resistance factors in equation 4 are identical to those used in equation 5.1. If it is assumed that equation 1 and 4 are both valid estimates of ET, then the two equations (gradient flux and generalized Penman-Monteith) can be equated to estimate one of the resistance factors.

Ortega-Farias et al. (2004), evaluated a methodology for calculating the canopy surface resistance ($r_{cv} \approx r_s$) in soybean and tomatoes, which is presented in equation 5.

$$r_s = \frac{\rho_a . c_p . VPD}{\Delta.(Rn - G))} . \frac{\theta_{FC} - \theta_{WP}}{\theta_i - \theta_{WP}} \tag{5}$$

where θ_{FC} and θ_{wp} are the volumetric moisture content at field capacity (fraction) and wilting point (fraction), respectively, and θ_{i} is a volumetric soil content in the root zone (fraction) measured each day.

Szeicz and Long (1969) describe a profile method to estimate r_s (equation 6). This method can be used in the field when the rate of evapotranspiration is measured by a lysimeter or calculated from the Bowen ratio, and the temperature, humidity and wind profiles are measured within the boundary layer simultaneously.

$$r_s = \frac{\rho_a . C_p , VPD}{\gamma . \lambda E} \tag{6}$$

The inverse of the equation 1 can be used to estimate an effective surface resistance when all the other parameter are known or measured (Monteith, 1995):

$$r_s = r_a . \frac{\left[\frac{\Delta(R_n - G) + \rho_a C_p \left(\frac{VPD}{r_a} \right)}{\lambda E} - \Delta - \gamma \right]}{\gamma} \tag{7}$$

MATERIALS AND METHODS

This research was carried out during 2006 and 2007 at the Experiment Station of the University of Puerto Rico in Juana Diaz, Puerto Rico, which is located in south central Puerto Rico, latitude 18°01'N, longitude 66°22'W longitude, and elevation 21 m above mean sea level, classified as a semi-arid climatic zone (Goyal and Gonzalez, 1989).

The field experiment had a plot size of 60 m x 117 m. This area was divided into two plots, one half received a water application rate sufficient to maintain the soil moisture content between 50% of the total soil available water and the field capacity (no drought stress) during the entire growing season. The second plot was submitted to drought stress at the beginning of the reproductive growth period. The water stress consisted of a 75% depletion in the total soil available water. Each plot (drought and non-drought treatments) was divided into 6 sub-plots of 9 m x 60 m. Two of the sub-plots were planted with common bean genotype 'SER 16' (6.5 plants.m^2) and four were planted with common bean genotype 'Morales' (13.5 plants.m^2) in 2006, and three sub-plots with each genotype were planted in 2007. Part of the neighboring plot was well irrigated grass, and irrigated fruit trees. The crop was irrigated two times per week to maintain the soil moisture near field capacity; the water stress was applied to half of the main plot after flowering began.

Fetch Requirements. The air passing over a surface is affected by the field surface feature (Rosenberg et al. 1983); the minimal fetch requirement was estimated based on the thickness of the internal boundary layer (δ in m) and a roughness parameter (Z_o in m) for each genotype considering the minimal and maximal crop height during the growing season. The δ was calculated using the relation proposed by Monteith and Unsworth (1990):

$$\delta = 0.15.L^{4/5}.Z_o^{\ 1/5} \tag{8}$$

where L is the distance of traverse (fetch) across a uniform surface with roughness Z_o. Z_o for crops is approximately one order of magnitude smaller than the crop height h, and was calculated using equation 9 (Rosenberg et al. 1983).

$$Log_{10}Z_0 = 0.997\log_{10}h - 0.883 \tag{9}$$

As a factor of safety, a height to fetch of 1:50 to 1:100 is usually considered adequate for studies made over agricultural crop surfaces (Rosenberg et al. 1983, Allen et al. 1998) but may be too conservative and difficult to achieve in practice. Alves et al. (1998) obtained full profile development using a 1:48 fetch relation in wheat and lettuce. Heilman et al. (1989) found that for Bowen-Ratio estimates a fetch 1:20 was sufficient over grass, and Fritschen and Fritschen (2005) obtained similar results. For this research, the height to fetch ratio was 1:32.

Data collection and instrumentation. Four Campbell Scientific weather stations were located in the four treatments plots: 'Morales' under non-stress, Morales under drought-stress, 'SER-16' under non-stress; and SER-16 under drought-stress. Each weather station measured net radiation with a Kipp & Zonen B.V. net radiometer (spectral range 0.2-100μm), wind direction and wind speed with a Wind Sensor-Met one 034B-L at 1.9 m; soil temperature with a TCAV averaging soil thermocouple probe at 0.08 m and 0.02 m depths, soil heat flux using soil heat flux plates at 0.06 m depth; volumetric soil moisture content with a CS616 water content reflectometer at 0.15 m depth; and air temperature and relative humidity with a HMP45C temperature and relative humidity probe at two height levels (0.20 m and 2.0 m). All sensors were connected to a CR10X data logger (Campbell Scientific, Inc).

An automated elevator device was developed for moving the temperature and relative humidity sensor (Temp/RH) between the two vertical positions. The device consisted of a plastic (PVC) frame with a 12 volt DC motor (1/30 hp) mounted onto the base of the frame. One end of a 2-m long chain was attached to the shaft of 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.

The values of λE used in equations 6 and 7 were estimated using the Bowen-ratio method (equation 10). This method combines measurements of certain atmospheric variables (gradients of temperature and vapor concentration) and available energy-net radiation and changes in stored thermal energy (Tanner, 1960; Lloyd, 1992).

$$\lambda E = \frac{(Rn - G)}{(1+\beta)} \tag{10}$$

where λE is latent-heat flux (Wm^2), and:

$$\beta = \gamma \frac{\Delta T}{\Delta e} \tag{11}$$

where γ is psychometric constant, ΔT is difference in air temperature at two heights (◦C) and Δe is the difference in vapor pressure at two heights (kPa). The two heights used were the same as for the ET-Station (0.2 m and 2 m).

The hourly Bowen ratio estimates were validated using the Payero et al. (2003) guidelines, where the fluxes with incorrect sign and $\beta \approx -1$ where not considered. Also the Monin-Obukhov stability factor (ζ) was calculated using equation 12 (Rosember et al. 1983; Campbell, 1985), flux with a negative sign for ζ were also excluded.

$$\xi = \frac{(-k.z.g.H)}{\left(\rho_a.C_p.T_a.u*^3\right)} \tag{12}$$

where k is von Karman's constant, z is height of wind and air temperature measurements (m), g is the gravitational constant (9.8 $m.s^{-2}$), $H = \beta\lambda E$, T_a is air temperature (^oK), u* is the friction velocity given by Kjelgaard et al. (1994) without the stability correction factor:

$$u* = \frac{k.u_z}{\ln\left(\frac{z - d + Z_{om}}{Z_{om}}\right)} \tag{13}$$

The crop height (h) was measured for each genotype each week, and, polynomial models were derived for each genotype and year, from which daily h values were interpolated. The r_a was calculated at one minute time intervals using equation 2. The r_L was measured with a Porometer type AP4-UM-3 (Delta-T Devices Ltd) in 2006 and Porometer model SC-1 (Decagon Devices, Inc.) in 2007, oncee per week at different time intervals from 7:00 am to 5:00 pm. The leaf area index was measured once per week using a non-destructive method (Ramirez et al., 2007). Undisturbed cores with soil samples were collected periodically to calibrate the moisture sensor readings. Hourly P-M ET estimates were calculated using four methods to determine r_s and compared to crop measurements. The methods were as follows:

PM-1: r_s was estimated from equation 3, called the "Measured method".
PM-2: r_s was estimated from equation 7, called the "Inverse method".
PM-3: r_s was measured from equation 5, called "Ortega-Faria method"
PM-4: r_s was measured from equation 6, called "Szeicz and Long method"
ET-Station: r_s was estimated from the equations 1 and 4, called "ET-Station method"

Evaluation of model performance. The performance of the models were evaluated using regression analysis, means, standard deviation (STD), the root mean square error (RMSE), and two model efficiency coefficients: the Nash and Sutcliffe (R^2) (Prenger et al. 2002), and the Legates and McCabe modified coefficient (E) (Tolk and Howell 2001).

RESULTS AND DISCUSSION

ET with r_s measured vs. ET by Bowen ratio. The daily ET with measured r_s (PM-1) agreed well with the Bowen ratio ET (equation 10 divided by λ) for both common bean genotypes, for a range of LAI, with and without moderate drought stress for both years. This conclusion is based on a t-test of b= ET_{PM}/ET_{Bowen}, which was determined not to be significantly different from 1. For SER 16 with drought stress (reduced soil moisture conditions and low LAI), the PM model over-estimated ET. In the case of Morales with drought stress, PM under-estimated ET in both years with b = 0.9 in 2006 and 0.7 in 2007. The under-estimation in 2007 was significantly different from 1, and was associated with high r_L during the drought stress, with a mean value of the 1226 $s.m^{-1}$ (1SD = 727 $s.m^{-1}$), as compared with SER16 with a mean r_L value of 584 $s.m^{-1}$ (1SD = 408 $s.m^{-1}$).

ET with r_s measured vs. ET with r_s estimated by micrometeorological variables. The models PM-3 and PM-4 were more closely related with the model PM-1, with the higher efficiency coefficients-$R^2_{\text{Nasch-Sutcliffe}}$ and E in both years, with and without drought stress. For Morales in 2006 with drought stress, the efficient coefficients $R^2_{\text{Nasch-Sutcliffe}}$ and E for PM-3 and PM-4 were >0.90 with slopes of the regression equations of 0.95 and 1.0 respectively, while the LAI was between 1.5 and 4.0.

The PM-3 value for Morales without drought stress in 2007, was $R^2_{\text{Nasch-Sutcliffe}}$ = 0.92 and the slope = 0.86, with the LAI between 0.1 and 3.0. When the drought stress was moderate, the $R^2_{\text{Nasch-Sutcliffe}}$ = 0.99 and slope = 0.95 with the LAI between 1.5 and 4.0.

PM-2 resulted in the lowest accuracy of ET estimation during both years. This situation is related with the aerodynamic resistance (r_a), which is included in both models for r_s. In the case of equation 7 for r_s, when all the other parameter are constant, if r_a increases then r_s also increases, and a high r_s decreases the ET. This situation was observed during: DOY 91, 2006 (r_a = 492 $s.m^{-1}$), DOY 46, 2007 (r_a =489 $s.m^{-1}$), DOY 71, 2007 (r_a = 220 $s.m^{-1}$, LAI= 2.6 m^2,m^{-2} and θ_v=0.22 $m^3.m^{-3}$). The results are contrary to observations in this study, as well as those reported by Alves and Pereira (2000), where the r_s was inversely related with r_a (Fig 1), which implies that with low r_a (windy conditions), the r_L (and therefore r_s) increases. The Alvers and Pereira (2000) study did not measure the r_L, the r_s was estimated based on micrometeorological parameters.

Disparities in the measured r_s using the PM-inverse (PM-2) arise from: a) imperfect sampling of leaves and the arbitrary method of averaging leaf resistance over the whole canopy, b) from the dependence of r_s on non-stomatal factors such as evaporation from wet soil or stems, or others and c) the complex aerodynamic behavior of canopies (Monteith, 1995).

When the drought stress was high, the difference among the models was evident, and especially in the low LAI case for DOY 64, 2007 and DOY 79, 2007 where PM-2, PM-4 and ET station were greater than PM-1, and PM- 3 was the lowest. This result was associated with the moisture content readings that were made at 15 cm, and the overestimation of r_s.

At low LAI (≤1.0) the differences among models was evident. The ET calculated by PM-1 was lower than that of PM-3, PM-4 and ET-Station (DOY 79, 2007) calculation. The differences between models can be associated with the effect of the local sources of sensible heat from non-evaporating surfaces such as dry soil surrounding transpiring plants (Ritchie, 1983).

When the LAI >1.0, and without moderate drought stress, all the models with the exception of PM-2 were closely related with PM-1. PM-2 was closely related with PM-1 and the other models when the ET rate during the day was low. When soil moisture decreased, r_s estimated with PM-3 and PM-4 models were the most closely related to PM-1.

The precision of r_s in this research was directly influenced by the various input parameters used as inputs in its estimation. The r_s estimated as a function of the R_n, G, VPD and soil moisture (PM-3) was closely related with the method estimated with VPD and λE (PM-4); overestimation was related with strong drought stress conditions, where the soil moisture at 15 cm approached the wilting point (WP). The overestimation of r_s in the PM-3 model can be partially explained by the fact that the soil moisture was measured only at 15 cm, and the depth of the roots at complete development extended to 35-40 cm. A similar situation is observed when the PM-3 and PM-1 were compared, indicating that the drought stress below 15 cm was not strong and the plants had more available water.

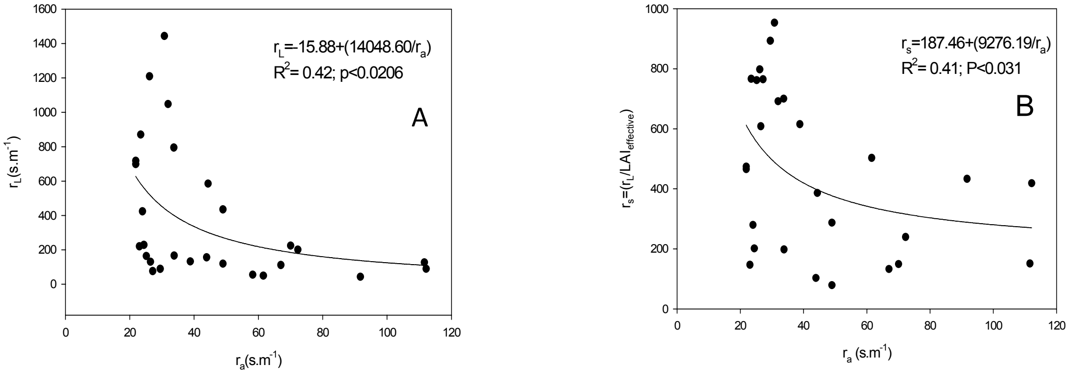

Figure. 1 Aerodynamic resistance (r_a) as a function of: **A**. Stomatal resistance (r_L) and **B.** Measured surface resistance (r_s).

The PM-2 model (inverse model) overestimated the r_s particularly when the aerodynamic resistance was high, due to r_a being in the numerator in the inverse model. This situation is not consistent with the measured data presented in Figure 1. The r_s by the PM-1 model (measured) was higher when the LAI was low, this situation is associated with the LAI being in the denominator. In those cases when the LAI < 2.0, the r_s increases geometrically. For example, when LAI = 0.5 the r_s is four times higher than r_L. In this study, the larger differences among r_s-models were observed when LAI <1.0.

The large differences early in the season; when the LAI <0.5, among the PM-1 model and the others, indicates that during the initial growth state all the leaves are effective in the transpiration process. This indicates that the use of the $LAI_{effective}$

when LAI < 1.0 is not necessary and tends to overestimate the r_s and under-estimate the ET.

CONCLUSIONS

This study indicates that crop evapotranspiration (ET_c) in common bean can be estimated in a one-step procedure using the Penman-Monteith model (PM) under drought stress and non-drought stress conditions, if the surface resistance (r_s) is appropriately parameterized. The model proposed in the Drainage and Irrigation Paper-FAO No. 56 (Allen et al. 1998), referred to in this study as the PM-1 model, gave reasonable ET estimates when the LAI was over 1.0, and in the genotypes with drought tolerance when strong drought conditions were present. The model proposed by Ortega-Farias et al. (2004) also provided good estimates of ET, with appropriate soil moisture readings under drought and non-drought conditions. The advantage of this model is that the stomatal resistance is not accounted for directly, but the surface resistance is estimated as a function of micrometerological parameters and soil moisture, that are directly related with stomatal control. The ET-Station gave good evapotranspiration estimation when LAI was over 1.0, without stress and/or with moderate drought stress. The inverse of the PM model did not estimate ET accurately under windy or dry conditions; conditions which directly influence the stomatal resistance.

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