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Single- and Dual-Surface Implicit Energy Balance Solutions for Reference ET

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Abstract. *The concept of a reference evapotranspiration (ET_r) calculated from daily or hourly weather data, multiplied by a crop coefficient, K_c, in order to estimate crop water use, ET_c, is widely established in agricultural science and engineering. To find region and variety-specific values of K_c from field-measured ET_c values, the equation is inverted to: $K_c = ET_c/ET_r$. Forms of the Penman-Monteith (PM) formula for calculation of reference alfalfa or grass evapotranpsiration (ET_r and ET_o, respectively), have been promulgated by ASCE in 1990, FAO in 1998 and ASCE in 2005. The PM formulations are sensitive to climatic conditions, producing estimates of ET_r and ET_o that are more or*

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less close to measured values depending on regional climate, and yielding values of K_c that vary from region to region and so are not transferrable. Theoretical shortcomings may be the basis of some of these problems, including the explicit nature of the calculation, which relies on the implied assumption that canopy and air temperatures are equal. We tested two surface energy balance formulations that stipulated different air and canopy temperatures, one a two-layer (soil and canopy) and one a one-layer (big leaf) approach but with soil heat flux included. Since canopy temperature is implicit in these formulations, they must be solved iteratively. Iterative solutions of ET_r were compared with the FAO and ASCE PM formulations and against lysimeter-measured ET_r. All three methods of ET_r estimation produced ET values that compared very well with field-measured ET for alfalfa grown under reference ET conditions. Errors may occur with any of the three approaches to ET_r estimation when stomatal resistance changes due to weather conditions; and assumptions of constant daytime and nighttime surface resistances thus cause mis-estimation of surface energy fluxes. It appears that a surface resistance value of 200 s m^{-1} at night for alfalfa grown under reference ET conditions is too large. It also appears that assuming constant daytime surface resistance of 30 s m^{-1} is probably not ideal, and that presenting daytime surface resistance as a function of vapor pressure deficit might improve ET_r prediction.

Keywords. Irrigation scheduling, Evapotranspiration, Penman-Monteith, Crop coefficient, Implicit solution.

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Introduction

Since Penman (1948) published his famous equation describing evaporation from wet surfaces based on the surface energy balance, there have been numerous developments, additions and refinements of the theory. Notable examples are the van Bavel (1966) formulation, which includes a surface roughness length term, z_0; and the Penman-Monteith (PM) formula (Monteith, 1965), which includes aerodynamic and surface resistances. The van Bavel equation tends to overestimate in windy conditions and is very sensitive to the value of z_0 (Rosenberg, 1969). Howell et al. (1994) compared several ET equations for well-watered, full cover winter wheat and sorghum and found that the PM formula performed best. The PM formula is widely used in agricultural and environmental research; and it has been presented by ASCE (Jensen et al., 1990; ASCE, 2005) and FAO (Allen et al., 1994a,b; 1998) as a method of computing estimates of reference evapotranspiration (ET_o) for use in the crop coefficient (K_c) paradigm where crop water use is estimated as $K_c \times ET_o$. The PM equation may be expressed as

$$\mathrm{LE} = -\frac{\Delta\left(R_\mathrm{n} + G\right) + \rho_\mathrm{a} C_\mathrm{p}\left(e_\mathrm{s} - e_\mathrm{a}\right)/r_\mathrm{a}}{\Delta + \gamma\left(1 + r_\mathrm{s}/r_\mathrm{a}\right)} \tag{1}$$

where LE is latent heat flux (which is converted to ET_o in mm), R_n is net radiation, and G is soil heat flux (all in MJ m^{-2} s^{-1} and all positive towards the surface); Δ is the slope of the saturation vapor pressure-temperature curve (kPa ºC^{-1}) commonly evaluated at air temperature (T_a), ρ_a is air density (kg m^{-3}), C_p is the specific heat of air (kJ kg^{-1} ºC^{-1}), e_a is vapor pressure of the air at reference measurement height z_m, and e_s is the saturated vapor pressure at a dew point temperature equal to the air temperature at z_m (kPa), (e_s - e_a) is the vapor pressure deficit, r_a is the aerodynamic resistance (s m^{-1}), r_s is the surface (bulk canopy) resistance (s m^{-1}), and γ is the psychrometric constant (kPa ºC^{-1}).

Penman's equation and those derived from it eliminated canopy temperature from energy balance considerations. Besides measurements of R_n and G, the user must know the vapor pressure of the air, e_a, and air temperature (from which e_s may be calculated) at reference measurement height, z_m (often 2 m). The use of e_s as a surrogate for the (unknown) sub-stomatal vapor pressure introduces the assumptions that osmotic potential of the leaf water has little affect on the vapor pressure and that the difference between air and canopy temperature does not introduce much error in the estimation of sub-stomatal vapor pressure. To the extent that these assumptions are not true, the errors are, for practical purposes, merged into the resistance terms, r_a and r_s, in Eq. (1) since estimates of these resistances tend to be based on fitting of Eq. (1) to field-measured data. The values of r_a and r_s are difficult to obtain. The value of r_a changes not only with wind speed and surface roughness, but also as atmospheric stability changes, which is itself affected by the canopy – air temperature difference and sign. The value of r_s is known for only a few crops and is dependent on plant height, leaf area, irradiance, water status of the plant, species and probably variety. If the value of r_s is obtained by inverting Eq. (1), it will include any errors due to the assumption that air and canopy temperatures are equal, plus any errors due to incorrect values of r_a.

Although important as a research model, the PM method is not much used for direct prediction of LE due to the difficulty of knowing r_a and r_s. However, it is commonly used to predict a theoretical reference evapotranspiration, ET_o for grass and ET_r for alfalfa, for use in irrigation scheduling (Allen et al., 1994ab). In this application crop water requirement, ET_c, is usually estimated from daily values of ET_r and a dimensionless crop coefficient, K_c, which is itself dependent on the crop variety and crop growth, and which is often taken as a function of time since planting or growing degree days.

$$ET_c = K_c ET_r \quad (2)$$

Crop coefficient values are determined from experiments that measure daily crop water use, ET_c, and that measure or, more commonly, estimate ET_r and then compute

$$K_c = ET_c/ET_r \quad (3)$$

Many details on this methodology are found in Jensen et al. (1990), Allen et al. (1998) and ASCE (2005).

Implicit-iterative estimates of latent heat flux

In order to avoid the limitations of the Penman (1948) approximation for (T_o - T_z), several efforts have focused on iterative or recursive solution of the surface energy balance equations, which are implicit in T_o, without resorting to any assumptions. It has long been recognized that only by iterative solution of the implicit energy balance equations can these be solved with complete accuracy (Budyko, 1958; Milly, 1991; Tracy et al., 1984; McArthur, 1992). Iterative solutions have been used in computer models of the general surface energy balance (Bristow, 1987), of evaporation from bare soil (Lascano and van Bavel, 1983, 1986) and of ET from plant and soil surfaces (Lascano et al., 1987; Evett and Lascano, 1993).

Even though iterative solutions have long been available on personal computers and even possible on hand-held calculators, they have not yet supplanted the PM approach for calculating reference evapotranspiration, ET_o. As an alternative to the PM equation, Lascano and van Bavel (2007) applied a recursive method, attributed to Budyko (1958), in which ET and T_o were found by iteration, satisfying the surface energy balance. Particularly when $T_a >> T_o$ and evaporative demand was large, the PM method underestimated reference ET by as much as 25%. They concluded that the PM method will underestimate ET in most cases, with the error increasing as evaporative demand increases (larger values of $T_a - T_o$ and smaller values of RH). Widmoser (2009) compared an iterative solution with the PM method and found the PM solutions for ET to deviate by as much as -40% to +9%, and that deviation was greater for smaller time steps (e.g. hourly versus daily). Negative errors were larger when T_a was larger, RH was smaller and the available energy ($R_n + G$) was smaller. Positive errors increased when RH and Ta were both large while ($R_n + G$) was small, or when ($R_n + G$) and T_a were both large and the ratio r_s/r_a was large (large surface resistance and small aerodynamic resistance; e.g., tall, stressed plants and windy conditions). These analyses give further insight into the problems encountered when transferring crop coefficients between regions with different climates when those K_c values were determined using PM based reference ET values. Lascano and Evett (2007) demonstrated the estimation of hourly values of the surface resistance, r_s, using measured weather data to calculate hourly ET for various values of r_s to develop a function ET(r_s), and interpolating against this function with hourly ET values measured by weighing lysimeter. They also showed that r_s could be found in a similar manner by computing surface temperature, T_s, for various values of r_s and interpolating against the function $T_s(r_s)$ with the measured surface temperature. Lascano et al. (2010) found that a recursive solution of the energy balance solved for r_s gave a mean daily value of 45 s m^{-1} for alfalfa grown under reference ET conditions at Bushland, Texas in 1999 (Evett et al., 2000). They called this the recursive combination method (RCM).

Standardized Penman-Monteith Formulation

Jensen et al. (1990) and Allen et al. (1994ab) presented methods of calculating LE for well-watered, full cover grass and alfalfa using Penman-Monteith formulations; and these were used

in recent studies at Bushland, Texas (Evett et al., 1998, 2000; Todd et al., 2000) that showed that ET of alfalfa grown under reference conditions (not lacking for water and nutrients, height ≥0.5 m, leaf area index ≥3) in that advective, semi-arid environment was well estimated, but ET of grass grown under reference conditions was not as well estimated. The latest standard PM formulation for a tall crop reference ET, ET_{sz}, is the ASCE Standardized Reference Evapotranspiration Equation, given for hourly computation as (ASCE, 2005)

$$ET_{sz} = \frac{0.408\Delta\left(R_n - G\right) + \gamma \frac{66}{T+273} u_2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + C_d u_2\right)} \tag{4}$$

where R_n is net radiation taken as positive towards the surface (big leaf) and has units of MJ m^{-2} h^{-1}; in contrast to Eq. [1], G is soil heat flux taken as positive away from the surface (same units); e_s, e_a, Δ, and γ are as defined for Eq. [1]; u_2 is hourly mean wind speed (m s^{-1}) at 2-m height measured over clipped (0.08-m high) grass; and C_d = 0.25 for R_n>0 and C_d = 1.7 for R_n≤0. Assumptions used in formulating this simplified equation were that the reference vegetation height was 0.5 m; air temperature and humidity were measured at 1.5 to 2.5 m height; the zero plane displacement height was 0.08 m; the latent heat of vaporization was 2.45 MJ kg^{-1}; the bulk surface resistance for R_n>0 (daytime) was 30 s m^{-1}; and the bulk surface resistance for R_n≤0 (nighttime) was 200 s m^{-1}. If wind speed is measured over vegetation taller than approximately 0.3 m, ASCE (2005) recommended that a form of the equation that allows computation of the zero plane displacement height be used. This is Equation [B.1] in ASCE (2005), which can be used to estimate alfalfa reference ET, ET_r

$$ET_r = \left[\frac{\Delta\left(R_n - G\right) + K_{time}\rho_a C_p \frac{\left(e_s - e_a\right)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \right] / \left(\lambda \rho_w\right) \tag{5}$$

where R_n has units of MJ m^{-2} per unit time period, τ_p; G, e_s, e_a, Δ, ρ_a, C_p, γ, r_s and r_a are as defined previously; λ is the latent heat of vaporization (MJ kg^{-1}); ρ_w is the density of water (kg m^{-3}); and K_{time} is a unit conversion factor that changes depending on the value and units of τ_p. For example, if τ_p is 1 hour, then K_{time} = 3600 s h^{-1}; if τ_p is 1 day, then K_{time} = 86,400 s d^{-1}.

The PM formulations are sensitive to climatic conditions, producing estimates of ET_r and ET_o that are more or less close to values measured on well-watered and fertilized alfalfa and grass (not otherwise stressed) depending on regional climate, and yielding values of K_c that vary from region to region and so are not transferrable. Theoretical shortcomings may be the basis of some of these problems, including the implicit nature of the calculation, which relies on the assumption that canopy and air temperatures are equal. Allen et al. (1994a) provided evidence for this lack of transferability by comparing the estimated ratio of alfalfa to grass reference ET across six arid and five humid locations. The ratio varied considerably across locations, most dramatically between arid and humid locations. For most locations there was also a difference between the ratio for the peak month and the mean ratio for that location. Note that this variance of ratios applies equally as well to the ratio of a particular crop ET to reference ET (i.e. the crop coefficient, ET/ET_r) thus calling into question the transferability of crop coefficients. Evett et al. (2000) compared alfalfa and grass PM reference ET formulas to measured ET for alfalfa and grass grown under reference ET conditions and found that the ratio of alfalfa to grass reference ET was not well predicted by the PM formulations for their windy, semi-arid advective environment, thus supporting the findings of Allen et al. (1994a). For a variety of different plant

heights and canopy resistances, Annandale and Stockle (1994) used an energy balance model to study variability of full-canopy-cover K_c, as influenced by changes in solar radiation, air temperature, the vapor pressure deficit (e_z - e_o^*), and wind speed. Variability in K_c increased as crop height increased and as r_s decreased. Variability in K_c decreased if an alfalfa reference ET was used rather than a grass reference ET; and they recommended: 1) using alfalfa reference ET, and 2) development of methods for directly estimating crop ET.

Motivated by the problems inherent in the Penman approximation and the problems of transportability of crop coefficients when they are derived using a PM formulation, we used the alfalfa data of Evett et al. (1998, 2000) to further investigate implicit solutions of the energy balance for estimation of reference alfalfa evapotranspiration, ET_r. Objectives were to (i) solve the energy balance iteratively for a single-surface, big-leaf model to find evapotranspiration (ET_{r1}), T_s and r_s, comparing ET_{r1} to measured ET (ET_m) and estimated surface temperature to measured values; (ii) solve the energy balance implicitly for a two-surface (soil and plant) model that calculates soil heat flux by finite difference, finding evapotranspiration (ET_{r2}); (iii) calculate ET_r using the ASCE 2005 standardized reference ET formulation; and (iv) contrast and inter-compare results from the three methods of calculating alfalfa ET for reference conditions.

Methods

Alfalfa was grown at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX (35° 11′ N, 102° 06′ W, 1170 m elevation above MSL) on a Pullman fine, mixed, superactive, thermic Torrertic Paleustoll. A detailed description of the sensors and methods used to measure the alfalfa growth and ET and weather variables is given by Evett et al. (2000), but a short description is given here. Half-hourly values of air (T_a) and dew-point (T_d) temperature, incoming short-wave irradiance (R_g) and wind-speed (U_z) were measured over an adjacent grass plot. Soil heat flux (G) and surface radiometric temperature (T_s) were measured at the site of a large weighing lysimeter in the alfalfa field. Data for 27 days with no rain in 1999 were selected and used as input data to calculate hourly values of ET. Half-hourly values of alfalfa ET were measured with large weighing lysimeters; lysimeter mass was measured every 0.5-h with 0.05-mm accuracy (Dusek et al., 1987: Howell et al., 1995). Alfalfa height was measured periodically; and a curve fit of height versus time after cutting or emergence from dormancy was used to estimate height on other days. Alfalfa variety Pioneer 5454[1] was seeded at a rate of 28 kg ha^{-1} in September 1995 with a grain drill on 0.2-m spacing operated in two perpendicular directions. Alfalfa was irrigated and fertilized to be well watered and without limitation of fertilizer or other inputs or management. Over the lysimeter, R_n was measured with net radiometers (model Q*5.5, REBS, Seattle, WA); and in the lysimeter G was measured with four heat flux plates (model HFT-1, REBS, Seattle, WA) buried 0.05-m below the surface with averaging thermocouples at 0.02- and 0.04-m depths above each plate. Also, T_s was measured with infrared thermometers (model IRtc2.0, Exergen, Watertown, MA USA). Data were screened so that reference conditions were represented (height ≥0.5 m, leaf area index ≥3) and to avoid days on which precipitation or irrigation occurred, days before the crop was fully recovered from winter dormancy and days affected by end-of-season cold or lack of irrigation, resulting in 27 days of alfalfa ET data for 1999.

[1] Mention of trade names or commercial products in this report is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Implicit single-surface energy balance solution

The single-surface or big leaf energy balance implicitly assumes a closed canopy and treats the canopy and soil surfaces as one

$$0 = \mathrm{ET}_{r1} + R_n + G + H \tag{6}$$

where R_n and G are as defined above except that both are taken as positive towards the surface; and H is the sensible heat flux (W m^{-2}), which is computed by

$$H = \frac{\rho_a c_p (T_a - T_s)}{r_{aH}} \tag{7}$$

where r_{aH} is the aerodynamic resistance to sensible heat flux, and T_a and T_s are the air and surface temperatures, respectively (ºC). Aerodynamic resistances for sensible and latent heat fluxes were assumed equal and were estimated for neutral atmospheric conditions from

$$r_a = \frac{1}{k^2 u_z}\left\{\ln\left(\frac{[z_m - d]}{z_{oH}}\right)\right\}^2 \tag{8}$$

where z_m (m) is the measurement height for wind speed, u_z (m/s), and air temperature; k is 0.41; z_{0H} is the roughness length for sensible heat transport; and d is the zero plane displacement height. The value of r_a calculated from Eq. (8) is too large for highly unstable conditions and too small for very stable conditions. Stability corrections can be made to Eq. (8) for those conditions (see Monteith and Unsworth, 1990, p. 234 for some examples), but were not made for this study.

The zero plane displacement height, d, was calculated as:

$$d = \frac{2}{3} h_c \tag{9}$$

where h_c is crop height (set to 0.50 m), and the roughness length for sensible heat transport was:

$$z_{0H} = 0.0123\, h_c \tag{10}$$

Net radiation, R_n, was calculated as

$$R_n = (1 - \alpha) R_s - \sigma\varepsilon (T_s + 273.2)^4 + R_L \tag{11}$$

where R_{si} is solar irradiance at the surface, α is the albedo or surface reflectance (taken as 0.23 for reference alfalfa conditions), ε is the surface emissivity (taken as 0.96 for reference alfalfa), σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), T_s is surface temperature (K), and the down-welling long wave radiation is

$$R_L = \sigma (T_a + 273.2)^4 \varepsilon_a \tag{12}$$

where ε_a is the sky emissivity and is calculated per Idso (1981) as

$$\varepsilon_a = 0.70 + 5.95 \times 10^{-4} e_a \quad \exp\left[\frac{1500}{T_a + 273.1}\right] \tag{13}$$

The evapotranspiration, ET_{r1}, was computed using a rate equation as

$$\mathrm{ET}_{r1} = \lambda (e_s - e_a) / (r_{av} + r_c) \tag{14}$$

where r_{av}=r_a, and the substomatal vapor pressure, e_s (kPa), was computed from the surface temperature, T_s (ºC), using Murray's (1967) equation

$$e_s = 0.61078 \quad \exp\left(\frac{17.269T_s}{237.3 + T_s}\right) \tag{15}$$

And, e_a is the vapor pressure of the air at reference height calculated from the dew point temperature, T_{dew}, as

$$e_a = 0.61078 \quad \exp\left(\frac{17.269T_{dew}}{237.3 + T_{dew}}\right) \tag{16}$$

Since the surface temperature is used in the calculation of ET_{r1}, R_n and H, the surface energy balance (Eq. (6)) is implicit in T_s and must be solved using an implicit equation solver. Lascano and Van Bavel (2007) used both the MathCad software (Mathsoft Engineering & Education, Inc., Cambridge, MA) and Microsoft© Excel 2002 for this iterative solution. Here, we used the implicit equation solver in the ENWATBAL software (Evett and Lascano, 1993). In keeping with Lascano et al. (2010), we term this the recursive combination method (RCM).

Implicit two-surface energy balance solution

A surface energy balance formulation that includes both soil and plant surfaces allows the energy balance of the soil to be solved separately, leading to calculation of a soil surface temperature, T_{ss}, which allows a mechanistic calculation of the soil heat flux. We used the ENWATBAL model, a mechanistic evapotranspiration model that separately and implicitly solves the energy balances of the soil and canopy surfaces (Evett and Lascano, 1993). ENWATBAL calculates the soil heat and water fluxes using finite difference solutions of the flux equations applied to a one-dimensional system of user-specified layers across up to ten soil horizons, also user specified. We used the default soil layering and horizonation found in the distribution version.

The governing equations in ENWATBAL are given in Evett and Lascano (1993) and are documented in the source code (available at http://www.cprl.ars.usda.gov/programs/index.htm), and only details relevant to the present study will be presented here. Most of these have to do with setting parameter and input values to represent a well-watered reference alfalfa crop. The model has leaf area index (LAI) as an input variable, and we specified LAI = 5.05 to represent a reference crop in keeping with Eq. B.6 of ASCE (2005). In keeping with the assumption that substomatal vapor pressure is affected only by surface temperature and is thus not diminished by leaf water potential, we set soil water content to values corresponding to soil water potentials of -33 kPa given the default tables of soil water content versus potential. Water content was reset to these field capacity values at each time step. In ENWATBAL, the canopy surface resistance, r_c, is computed as

$$r_c = 1/(c_L \times \mathrm{LAI}) \tag{17}$$

where LAI is leaf area index (dimensionless) and c_L is

$$c_L = \frac{2}{1/c_{L1} + 1/c_{L2}} \tag{18}$$

where c_{L1} is a function of leaf water potential, Ψ_L, and c_{L2} is a function of solar irradiance. To achieve daytime and nighttime values of r_c equivalent to those specified in ASCE (2005), we set c_{L1}= f(Ψ_L) to 0.0066, c_{L2} = f(R_s) to 0.0066 and LAI = 5.05, resulting in r_c = 30 s m^{-1} during daylight. During nighttime, we set c_{L1}= f(Ψ_L) to 0.0066, c_{L2} = f(R_s) to 0.000535 and LAI = 5.05, resulting in r_c = 200 s m^{-1}.

ASCE Standardized Penman-Monteith solution

The ""full-form"" ASCE standardized Penman-Monteith alfalfa reference ET, ET_r, for full-cover (LAI=5.05), 0.5-m tall alfalfa (ASCE, 2005) was calculated with the REF-ET computer program (Allen, 2002) using half-hourly mean weather data (R_s, u_z, T_a, and RH).

Results

Lysimeter-measured daily ET for alfalfa grown under reference conditions ranged from 2.6 to 12.7 mm for the data shown here. Daily ET values as large as 18 mm were measured for this alfalfa crop at Bushland in 1998 (Evett et al., 2000). The ASCE PM method estimated daily alfalfa ET well when compared with lysimeter-measured ET grown under reference conditions in 1999 (Fig. 1, left). There was some under estimation at large and small daily ET values, and some over estimation at mid-range ET values. The ENWATBAL two-layer model estimated daily alfalfa ET nearly identically to the ASCE PM method, producing a slope of 0.93 and offset of 0.4 mm (r^2 = 0.97 and RMSE = 0.45 mm for ENWATBAL vs. r^2 = 0.96 and RMSE = 0.51 mm for ASCE PM). Regression of ENWATBAL-predicted ET_r against ASCE PM ET_r produced a slope of 1.00, offset of <0.1 mm, and RMSE of 0.23 mm (Fig 1, right)

Lascano et al. (2010) computed the RCM using hourly data and estimated alfalfa reference ET in much the same way as did ENWATBAL and the ASCE PM method, but with more scatter (RMSE = 0.70 mm, r^2 = 0.91, r_c = 0.45 s m^{-1}) (Fig. 2, left). There was some under estimation of ET_r at large values. Computing the RCM using half-hourly data produced nearly identical results as did the RCM using hourly data (Fig. 2, right). Computing the RCM using half-hourly data and a daytime r_c value of 30 s m^{-1} rather than 45 s m^{-1} resulted in some over estimation of ET_r at large values ($ET_r = 1.05ET_{lys} + 0.07$, RMSE = 0.64 mm, r^2 = 0.95, data not shown), indicating that the correct daytime r_c value was between 30 and 45 s m^{-1}, as suggested by the hour of day

(t_h) dependent equation of Lascano et al. (2010) ($r_c = 0.7657 \times t_h^2 - 20.934 \times t_h + 173.93$, r^2 =

0.80).

Half-hourly fluxes of sensible and latent heat and of net radiation and soil heat flux were compared between the ENWATBAL estimates and lysimeter-measured values (sensible heat flux for the lysimeter was computed as the residual of the energy balance equation using measured latent heat flux, soil heat flux and net radiation) (Fig. 3). The closest estimate of lysimeter ET was on day of year (DOY) 177 when lysimeter ET was 8.87 mm and the ENWATBAL-estimated ET was 8.88 mm (Fig. 3A). Lysimeter *G* and *H* were well estimated by ENWATBAL during daytime, but Rn was over estimated and the magnitude of LE was over estimated (more negative values of LE from ENWATBAL in Figure 3A). After sunset, *H* was under estimated by up to 100 W m^{-2} by ENWATBAL and the magnitude of LE was under estimated as well. Therefore, the close agreement between daily ENWATBAL and lysimeter-measured ET was a result of compensating errors. Advection of energy caused considerable

nighttime alfalfa ET, a phenomenon that has been documented by Tolk et al. (2006) for this location.

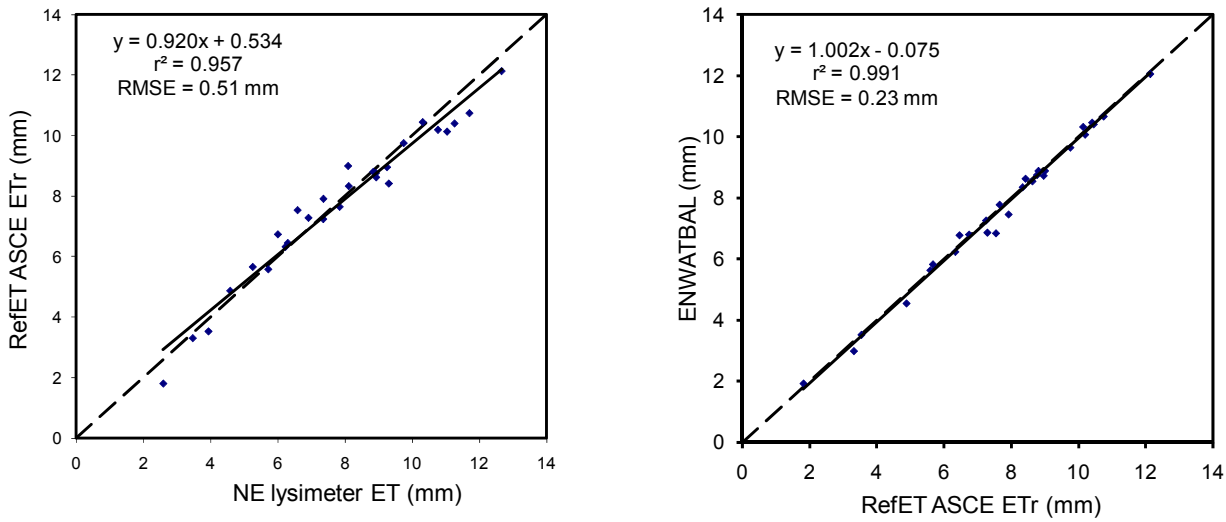

Figure 1. (Left) Daily reference alfalfa evapotranspiration (ET) estimated using the ASCE (2005) standardized Penman Monteith method (RefET ET_r) compared with lysimeter-measured daily ET of alfalfa grown under reference ET conditions. (Right) Daily reference alfalfa ET estimated using ENWATBAL compared with that estimated using the ASCE standardized Penman Monteith method (ET_r).

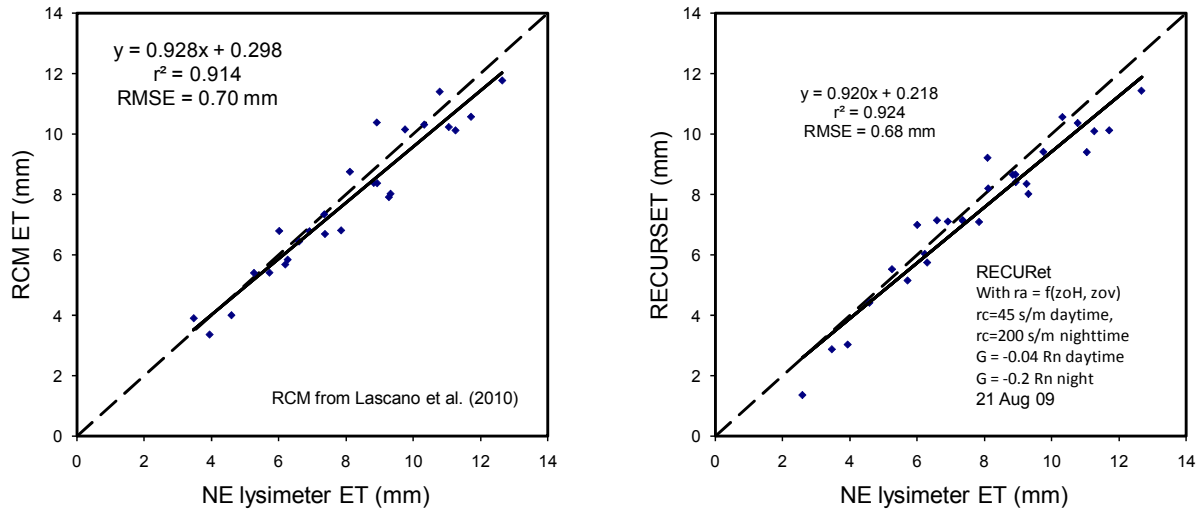

Figure 2. (Left) Daily evapotranspiration (ET) calculated using the recursive combination method (RCM) applied to hourly data (Lascano et al., 2010) compared to lysimeter-measured daily alfalfa water use for alfalfa grown under reference conditions at Bushland, Texas in 1999. (Right) Daily ET calculated using the recursive combination method (RECURSET) applied to

half-hourly data compared with the same measured daily alfalfa water use.

The largest positive error in ET estimation occurred on DOY 250 when ENWATBAL estimated a daily ET of 8.91 mm compared with lysimeter-measured ET of 8.09 mm (Fig. 3B). ENWATBAL under estimated *H* early in the daytime hours and over estimated Rn. Then late in the daytime hours, *H* was over estimated while Rn estimates matched measurements. Throughout the daytime hours, ENWATBAL over estimated the magnitude of LE. DOY 250 was the driest day in this dataset, with RH of 48%, and it was the seventh warmest with a mean air temperature of 24.5 °C (Table 1). Solar radiation was near the median value, and so was mean wind speed (3.9 m s^{-1}). If the large vapor pressure deficit caused alfalfa stomatal resistance to increase, which is possible, then the surface resistance would have been larger than the average value of 30 s m^{-1} assumed here. The large vapor pressure deficit would have accentuated the effect of a surface resistance value that was too small, resulting in over estimation of ET.

The largest negative error in estimation by ENWATBAL occurred on DOY 186 when lysimeter-measured ET was 11.71 mm and ENWATBAL ET estimate was 10.66 mm (Fig. 3C). Total solar irradiance for the day was the fourth largest at 30.5 MJ m^{-2}, and wind speed averaged the fifth greatest at 5.5 m s^{-1}, while RH was relatively low (61 %) and mean temperature was relatively high (24.5 °C) (Table 1). ENWATBAL under estimated *H* at night and for most of the daytime, probably due to over estimation of canopy temperature. Low estimates of the magnitude of nighttime LE as compared with lysimeter-measured LE accounted for most of the under estimation of daily ET.

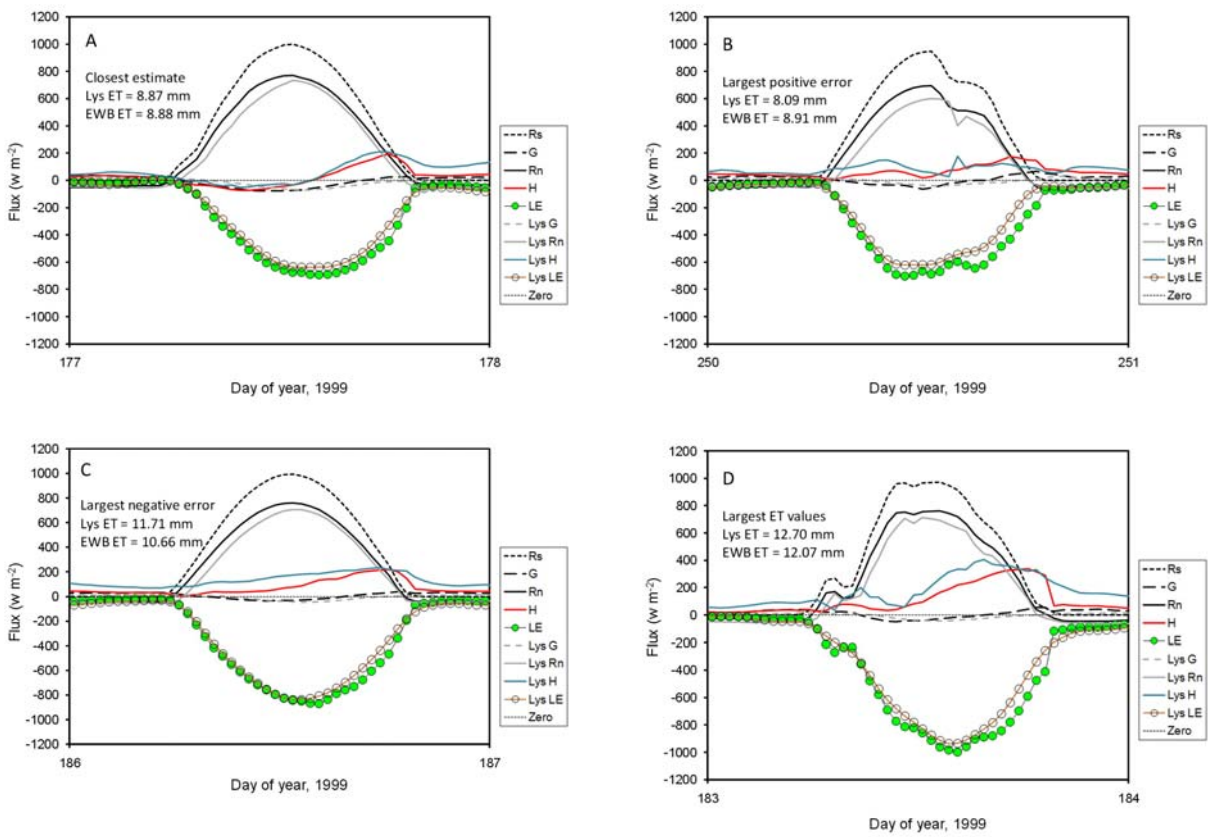

Figure 3. Energy fluxes and daily evapotranspiration (ET) values in mm as estimated by

ENWATBAL (EWB) (Evett and Lascano, 1993) and as measured at a weighing lysimeter (Lys) for (A) the day when the 24-h ET estimate most closely matched the lysimeter measurement, (B) the day when ET was over estimated the most, (C) the day when the ET was under estimated the most, and (D) the day when both estimated and measured ET were the largest.

In this data set, the largest lysimeter-measured ET value was 12.7 mm and occurred on DOY 183 (Fig. 3D). The ENWATBAL estimate of ET was 5% less than the measured value, and *H* was under estimated for most of the daytime and nighttime. As was evident for DOY 177 and 186, *H* was particularly under estimated in the hours after sunset. In this setting, the abrupt change of surface resistance from a value of 30 s m^{-1} in daytime to 200 s m^{-1} at night is unrealistic.

Conclusion

Both a recursive solution of the combination equation for surface energy balance (Lascano et al., 2010) and the ENWATBAL model of the two-layer (soil and plant canopy) energy balance successfully estimated evapotranspiration (ET) of alfalfa grown under reference ET (ET_r) conditions. The two-layer model was slightly better and was an excellent match for the ASCE standardized Penman Monteith ET_r method. The results examined here exemplify the kinds of errors that may occur with any of the three approaches to ET_r estimation when stomatal resistance changes due to weather conditions; and assumptions of constant daytime and nighttime surface resistances thus cause mis-estimation of surface energy fluxes. It appears that a surface resistance value of 200 s m^{-1} at night for alfalfa grown under reference ET conditions is too large. It also appears that assuming constant daytime surface resistance of 30 s m^{-1} is probably not ideal, and that presenting daytime surface resistance as a function of vapor pressure deficit might improve ET_r prediction.

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Table 1. Daily mean weather variables, including relative humidity (RH) and total daily solar irradiance (Rs), along with daily values of lysimeter-measured (NE Lys) alfalfa evapotranspiration (ET), reference alfalfa ET (ETr) estimated by ENWATBAL and ET estimation by the ASCE standardized Penman-Monteith (PM) method (ASCE, 2005) for each day of year (DOY). Maximum values of each are highlighted in yellow.

DOY	Mean wind speed ($m\ s^{-1}$)	Mean air temperature (°C)	Mean RH (%)	Total Rs ($MJ\ m^{2}$)	NE Lys ETr (mm)	RCM ETr (mm)	ASCE PM ETr (mm)
143	3.73	17.7	70.3	24.1	5.71	5.64	5.59
148	1.89	14.8	82.3	24.3	4.58	4.54	4.88
150	3.48	20.4	65.4	30.9	9.25	8.73	8.96
151	2.21	20.9	60.9	25.8	6.93	6.86	7.29
152	3.22	19.2	50.8	32.0	8.12	8.36	8.34
167	4.69	15.8	73.6	29.1	6.30	6.81	6.46
169	5.56	20.5	69.4	23.2	7.35	7.48	7.92
170	2.89	21.9	62.2	23.2	6.58	6.83	7.54
173	5.06	22.1	78.8	29.9	7.85	7.77	7.65
177	4.45	24.6	71.3	30.2	8.87	8.88	8.81
178	4.23	27.6	54.8	28.9	10.78	10.03	10.20
180	4.62	25.0	61.5	30.6	11.29	10.47	10.41
182	4.60	24.2	70.3	29.3	9.31	8.62	8.42
183	6.45	26.4	59.6	28.5	12.70	12.07	12.14
185	6.60	24.3	63.2	30.1	11.04	10.32	10.14
186	5.49	24.5	61.3	30.5	11.71	10.66	10.75
206	3.68	25.6	52.3	28.7	10.32	10.41	10.45
212	4.23	25.2	54.9	27.0	8.94	8.75	8.77
213	3.50	21.3	73.8	24.3	6.21	6.22	6.33
219	2.75	23.9	70.9	27.7	7.36	7.24	7.25
223	3.86	24.3	62.4	26.0	8.95	8.56	8.63
248	3.24	19.9	69.5	23.9	5.25	5.84	5.67
250	3.92	24.5	47.8	25.4	8.09	8.91	9.00
251	4.78	18.6	72.1	8.6	3.46	3.02	3.31
253	5.32	23.0	55.1	23.3	9.76	9.70	9.76
254	3.04	21.9	63.1	23.1	6.00	6.80	6.74
255	4.81	15.3	75.5	12.4	3.94	3.56	3.54
263	5.67	11.1	91.1	10.3	2.60	1.95	1.81
				Sum (mm):	219.2	215.0	216.7

References

Allen, R.G. 2002. REF-ET computer program. Version 2.01.17, dated 24 June 2002. The University of Idaho (available at http://www.kimberly.uidaho.edu/ref-et/) (Checked 25 April 2010).

Allen, R.G., M. Smith, A. Perrier, and L.S. Pereira. 1994a. An update for the definition of reference evapotranspiration. *ICID Bulletin* 43(2):1-34.

Allen, R.G., M. Smith, A. Perrier, and L.S. Pereira. 1994b. An update for the calculation of reference evapotranspiration. *ICID Bulletin* 43(2):35-92.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. *FAO Irrigation and Drainage Paper 56.* FAO, Rome, Italy.

Annandale, J.G., and C.O. Stockle. 1994. Fluctuation of crop evapotranspiration coefficients with weather: A sensitivity analysis. *Irrig. Sci.* 15(1):1-7.

ASCE. 2005. The ASCE Standardized Reference Evapotranspiration Equation. R.G. Allen, I.A. Walter, R.L. Elliott, T.A. Howell, D. Itenfisu, M.E. Jensen, and R.L. Snyder, R.L. (eds). Am. Soc. Civil Engr., Reston, VA.

Bristow, K.L. 1987. On solving the surface energy balance equation for surface temperature. *Agric. Forest Meteorol.* 39:49-54.

Budyko, M.I. 1958. The heat balance of the Earth's surface. (English translation by N.A. Stepanova.) U.S. Department of Commerce, Washington, DC.

Dusek, D.A, T.A. Howell, A.D. Schneider, and K.S. Copeland. 1987. Bushland weighing lysimeter data acquisition systems for evapotranspiration research. ASAE Meeting Paper no. 87-2506. International Winter Meeting of the American Society of Agricultural Engineers. Dec. 15-18. Chicago.

Evett, S. R., and R.J. Lascano. 1993. ENWATBAL.BAS: A mechanistic evapotranspiration model written in compiled BASIC. *Agron. J*. 85(3):763-772.

Evett, S.R., T.A. Howell, R.W. Todd, A.D. Schneider, and J.A. Tolk. 1998. Evapotranspiration of irrigated alfalfa in a semi-arid environment. ASAE Paper No. 98-2123. American Society of Agricultural Engineers.

Evett, S.R., T.A. Howell, R.W. Todd, A.D. Schneider, and J.A. Tolk. 2000. Alfalfa reference ET measurement and prediction. Pp. 266-272 In Robert G. Evans, Brian L. Benham, and Todd P. Trooien (ed) Proceedings of the 4th Decennial National Irrigation Symposium, Nov. 14-16, Phoenix, AZ.

Howell, T.A., J.L. Steiner, A.D. Schneider, S.R. Evett, and J.A. Tolk. 1994. Evapotranspiration of irrigated winter wheat, sorghum and corn. ASAE paper no. 94-2081. American Society of Agricultural Engineers.

Howell, T.A., A.D. Schneider, D.A. Dusek, T.H. Marek, and J.L. Steiner. 1995. Calibration and scale performance of Bushland weighing lysimeters. *Trans. ASAE* 38(4):1019-1024.

Idso, S.B. 1981. A set of equations for full spectrum and 8- to 14-μm and 10.5- to 12.5-μm thermal radiation from cloudless skies. *Water Resour. Res*. 17(2)295-304.

Jensen, M.E., R.D. Burman, and R.G. Allen (ed). 1990. Evapotranspiration and Irrigation Water Requirements. *ASCE Manuals and Reports on Engineering Practices No. 70*, ASCE, New York.

Lascano, R.J., and C.H.M. van Bavel. 1983. Experimental verification of a model to predict soil moisture and temperature profiles. *Soil Sci. Soc. Am. J.* 47:441–448.

Lascano, R.J., and C.H.M. Van Bavel. 1986. Simulation and measurement of evaporation from a bare soil. *Soil Sci. Soc. Am. J.* 50: 1127–1132.

Lascano, R.J., C.H.M. van Bavel, J.L. Hatfield, and D.R. Upchurch. 1987. Energy and water balance of a sparse crop: simulated and measured soil and crop evaporation. *Soil Sci. Soc. Am. J.* 51:1113-1121.

Lascano, R.J. and S.R. Evett. 2007. Experimental verification of a recursive method to calculate evapotranspiration. Conf. Proc. 28th Annual International Irrigation Show December 9-11, 2007, San Diego Convention Center. Irrigation Association. pp. 687-705.

Lascano, R.J., and C.H.M. van Bavel. 2007. Explicit and recursive calculation of potential and actual evapotranspiration. *Agron. J.* 99:585-590.

Lascano, R.J., C.H.M. van Bavel, and S.R. Evett. 2010. A field test of recursive calculation of crop evapotranspiration. Trans. ASABE. 53(4)(page numbers not available).

McArthur, A.J. 1992. The Penman form equations and the value of Delta: A small difference of opinion or a matter of fact? *Agric. For. Meteorol.* 57:305–308.

Milly, P.C.D. 1991. A refinement on the combination equations for evaporation. *Surv. Geophys.* 12:145–154.

Monteith, J.L. 1965. Evaporation and the environment. In The State and Movement of Water in Living Organisms. *XIXth Symp. Soc. for Exp. Biol.*, Swansea, Cambridge University Press. pp. 205-234.

Monteith, J.L., and M.H. Unsworth. 1990. Principles of Environmental Physics, 2nd Ed. Edward Arnold, London.

Murray, F.W. 1967. On the computation of saturation vapor pressure. *J. Applied Meteorol.* 6(1):203-204.

Penman, H.L. 1948. Natural evapotranspiration from open water, bare soil and grass. *Proc. R. Soc. London Ser. A*. 193:120-145.

Rosenberg, N.J. 1969. Seasonal patterns of evapotranspiration by irrigated alfalfa in the Central Great Plains. *Agron. J.* 61(6):879-886.

Todd, R.W., S.R. Evett, and T.A. Howell. 2000. The Bowen ratio-energy balance method for estimating latent heat flux of irrigated alfalfa evaluated in a semi-arid, advective environment. *Agric. Forest Meteorol.* 103(2000):335-348.

Tolk, J.A., S.R. Evett, and T.A. Howell. 2006. Advection influences on evapotranspiration of alfalfa in a semiarid climate. Agron. J. 98:1646-1654.

Tracy, C.R., F.H. van Berkum, J.S. Tsuji, R.D. Stevenson, J.A. Nelson, B.M. Barnes, and R.B. Huey. 1984. Errors resulting from linear approximations in energy balance equations. *J. Therm. Biol.* 9:261–264.

van Bavel, C.H.M. 1966. Potential evaporation: The combination concept and its experimental verification. *Water Resour. Res*. 2:455-467.

Widmoser, P. 2009. A discussion on and alternative to the Penman-Monteith equation. *Agric. Water Manage.* 96:711-721.