SINGLE- AND DUAL-SURFACE ITERATIVE 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, and 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 evapotranspiration (ET_r and ET_o, respectively) were 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 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 examined the ET_r estimation of two surface energy balance formulations that stipulated different air and canopy temperatures: a two-layer (soil and canopy) approach, and a one-layer (big leaf) approach that included soil heat flux. Since canopy temperature is implicit in these formulations, they must be solved iteratively. Iterative solutions of ET_r were compared with the ASCE PM formulation 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; thus, assumptions of constant daytime and nighttime surface resistances 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 calculation.*

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

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_o), 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 sensitive to the value of z_o (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; Allen et al., 2005) and FAO (Allen et al., 1994a, 1994b, 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 $K_c \times ET_o$ or $K_c \times ET_r$. The PM equation may be expressed as:

$$\mathrm{LE} = -\frac{\Delta(R_n + G) + \rho_a C_p (e_s - e_a)/r_a}{\Delta + \gamma(1 + r_s/r_a)} \qquad (1)$$

where

LE = latent heat flux (MJ m^{-2} s^{-1}, positive toward the surface), which may be converted to ET_o in mm

R_n = net radiation (MJ m^{-2} s^{-1}, positive toward the surface)

G = soil heat flux (MJ m^{-2} s^{-1}, positive toward the surface)

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Δ	=	slope of the saturation vapor pressure-temperature curve (kPa °C^{-1}) commonly evaluated at air temperature (T_a)
ρ_a	=	air density (kg m^{-3})
C_p	=	specific heat of air (kJ kg^{-1} °C^{-1})
e_a	=	vapor pressure of the air at reference measurement height z_m (kPa)
e_s	=	saturated vapor pressure at a dewpoint temperature equal to the air temperature at z_m (kPa)
$(e_s - e_a)$	=	vapor pressure deficit (kPa)
r_a	=	aerodynamic resistance (s m^{-1})
r_s	=	surface (bulk canopy) resistance (s m^{-1})
γ	=	psychrometric constant (kPa °C^{-1}).

Penman's equation and those derived from it eliminated canopy temperature (T_c) from energy balance considerations and avoided consideration of the soil surface temperature and the energy balance at the soil surface, instead considering the canopy-soil system as a "big leaf" with temperature T_o. In addition to the values of R_n and G, a user must know e_a and T_a (from which e_s may be calculated) at z_m (often 2 m). The use of e_s as a surrogate for the (unknown) substomatal vapor pressure introduces the assumptions that the osmotic potential of the leaf water has little effect on the vapor pressure and that the difference between T_a and T_c does not introduce much error in the estimation of substomatal 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 equation 1, since estimates of these resistances tend to be based on fitting equation 1 to field-measured data. The values of r_a and r_s are difficult to obtain. The value of r_a changes with wind speed, z_o, and atmospheric stability, and the stability is itself affected by the $(T_c - T_a)$ 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 equation 1, then it will include any errors due to the assumption that T_a and T_c are equal, plus any errors due to incorrect values of r_a.

Although important as a research model, the PM method is seldom used for direct calculation of LE due to the difficulty of knowing r_a and r_s. However, it is commonly used to calculate a theoretical reference evapotranspiration, ET_o for grass and ET_r for alfalfa, for use in irrigation scheduling (Allen et al., 1994a, 1994b). In this application, crop evapotranspiration (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, i.e.:

$$\mathrm{ET}_c = K_c \times \mathrm{ET}_r \tag{2}$$

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:

$$K_c = \mathrm{ET}_c/\mathrm{ET}_r \tag{3}$$

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

Implicit-Iterative Estimates of Latent Heat Flux

In order to avoid the limitations of the Penman (1948) approximation for $(T_o - T_a)$, 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, 1956; 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 (e.g., the ENWATBAL model; Lascano et al., 1987; Evett and Lascano, 1993).

Even though iterative solutions have long been available on personal computers and even possible on handheld calculators, they have not yet supplanted the PM approach for calculating reference ET. As an alternative to the PM equation, Lascano and van Bavel (2007) applied a recursive method, attributed to Budyko (1956), 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, i.e., larger values of $(T_a - T_o)$ and smaller values of relative humidity of the air. Widmoser (2009) compared an iterative solution with the PM method and found that the PM solutions for ET deviated by as much as –40% to +9%, and that the deviation was greater for smaller time steps (e.g., hourly vs. 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 T_a 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 K_c values between regions with different climates when those K_c values were determined using PM-based reference ET values. Lascano and Evett (2007) and Lascano et al. (2010) 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 the function ET(r_s) and interpolating against this function with hourly ET values measured with a 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. (1994a, 1994b) presented methods of calculating LE for well-watered, full cover grass and alfalfa using PM formulations, and these methods 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 $\geq$0.5 m, leaf area index $\geq$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 (Allen et al., 2005):

$$\mathrm{ET}_{sz} = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \tag{4}$$

where R_n is net radiation (MJ m^{-2} h^{-1}) taken as positive toward the surface (big leaf). In contrast to equation 1, G is soil heat flux (MJ m^{-2} h^{-1}) taken as positive away from the surface. The terms e_s, e_a, Δ, and γ are as defined for equation 1; u_2 is hourly mean wind speed (m s^{-1}) at 2 m height measured over clipped (0.08 m high) grass; C_n is 0.66; and C_d is 0.25 for $R_n > 0$ and 1.7 for $R_n \leq 0$.

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 $R_n \leq 0$ (nighttime) was 200 s m^{-1}. If wind speed is measured over vegetation taller than ~0.3 m, Allen et al. (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 Allen et al. (2005), which can be used to estimate alfalfa reference ET, ET_r:

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

where R_n has units of MJ m^{-2} per unit time period τ_p; the terms 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 (e.g., if τ_p is 1 h, then K_{time} = 3600 s h^{-1}; if τ_p is 1 day, then K_{time} = 86,400 s d^{-1}). Calculation of the zero plane displacement height is necessary in the computation of r_a, as shown in Appendix B of Allen et al. (2005).

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 T_c and T_a are equal (Evett et al., 2012). 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 estimated 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, T_a, $(e_s - e_a)$, and u. 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 Annandale and Stockle (1994) 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 ET, ET_r. Objectives were to: (1) solve the energy balance iteratively for a single-surface, big-leaf model to find evapotranspiration (ET_{r1}), T_s and r_s; (2) 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}); (3) calculate ET_r using the ASCE 2005 standardized reference ET formulation and the ASCE full-form reference ET (Allen et al., 2005); and (4) 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, Texas (35° 11′ N, 102° 6′ 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 dewpoint temperature (T_d), incoming shortwave irradiance (R_g), and wind speed (U_z) were measured over an adjacent short 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 vs. time after cutting or emergence from dormancy was used to estimate height on other days. Alfalfa variety Pioneer 5454 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, Wash.). In the lysimeter, G was measured with four heat flux plates (model HFT-1, REBS, Seattle, Wash.) buried 0.05 m below the surface with averaging thermocouples at 0.02 and 0.04 m depths above each plate. In addition, T_s was measured with infrared thermometers (model IRtc2.0, Exergen, Watertown, Mass.). Data were screened so that reference conditions were represented (height $\geq$0.5 m, leaf area index $\geq$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.

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 toward the surface, and H is the sensible heat flux (W m^{-2}), also taken as positive toward the surface, 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 (°C). 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^{-1}) and air temperature, k is 0.41, z_{0H} is the roughness length (m) for sensible heat transport, and d is the zero plane displacement height. The value of r_a calculated from equation 8 is too large for highly unstable conditions and too small for very stable conditions. Stability corrections can be made to equation 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:

$$d = \frac{2}{3} h_\mathrm{c} \tag{9}$$

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 downwelling 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:

$$\varepsilon_a = 0.70 + 5.95\times10^{-4} e_a \quad \exp\left[\frac{1500}{T_a + 273.1}\right] \tag{13}$$

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 (°C), using Murray's (1967) equation:

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

and e_a is the vapor pressure of the air at reference height, calculated from the dewpoint temperature (T_d) as:

$$e_a = 0.6107\ \exp\left(\frac{17.269 T_d}{237.3 + T_d}\right) \tag{16}$$

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 MathCad (Mathsoft Engineering and Education, Inc., Cambridge, Mass.) 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 G. We used the ENWATBAL model, a mechanistic ET 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 by Evett and Lascano (1993) and are documented in the source code (available at: www.cprl.ars.usda.gov/swmru-software-ewbes.php), and only details relevant to the present study are 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 equation B.6 of Allen et al. (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 by Allen et al. (2005), we set $c_{L1} = f(\Psi_L)$ 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 $c_{L1} = f(\Psi_L)$ 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

Both the standardized ASCE Penman-Monteith alfalfa reference ET (ET_{r_st}) and the full-form ASCE Penman-Monteith alfalfa reference ET (ET_{r_full}) for full cover (LAI = 5.05), 0.5 m tall alfalfa (Allen et al., 2005) were calculated using the REF-ET computer program (Allen, 2002) with half-hourly mean weather data (R_s, u_z, T_a, and relative humidity, RH). Preliminary results showed that the two formulations were practically equivalent (ET_{r_full} = 0.9951ET_{r_st} – 0.0097, r^2 = 0.9999), so only the standardized ET_r values are reported here and will hereafter be called ASCE PM.

Results

Lysimeter-measured daily ET for alfalfa grown under reference conditions ranged from 2.6 to 12.7 mm for the data discussed here. Daily ET values as large as 18 mm were measured for this alfalfa crop at Bushland, Texas, 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. 1a). There was some underestimation at large and small daily ET values, and some overestimation at midrange 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-calculated 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. 1b).

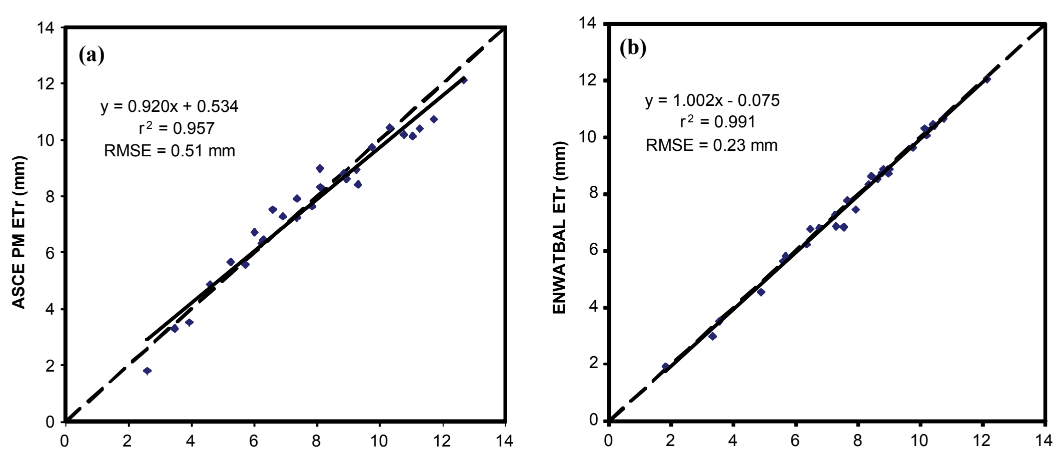

Figure 1. (a) Daily reference alfalfa evapotranspiration (ET_r) estimated using the ASCE standardized Penman Monteith method (ASCE PM; Allen et al., 2005) compared with lysimeter-measured daily ET of alfalfa grown under reference ET conditions, and (b) daily reference alfalfa ET estimated using ENWATBAL compared with that estimated using the ASCE standardized Penman Monteith method.

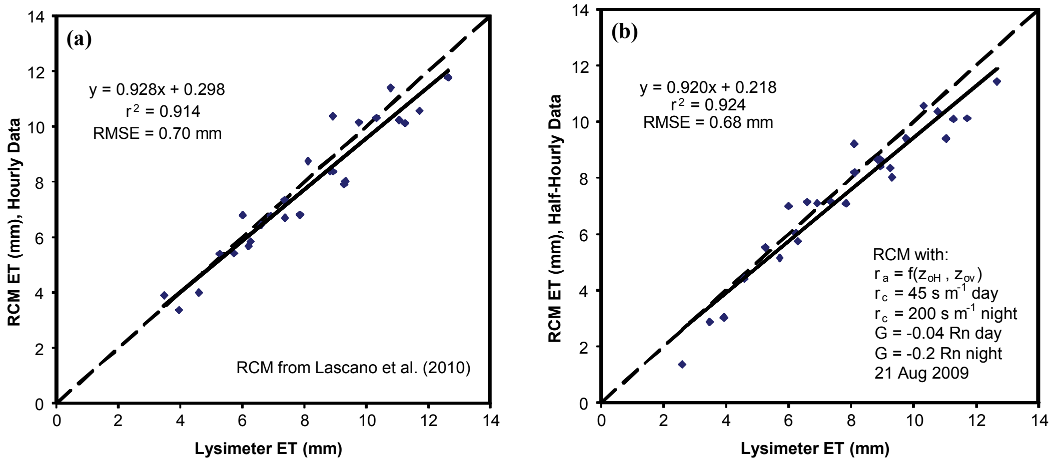

Figure 2. (a) Daily ET calculated using the recursive combination method (RCM) applied to hourly data (Lascano et al., 2010) compared to lysimeter-measured daily alfalfa water use for alfalfa grown under reference conditions at Bushland, Texas, in 1999, and (b) daily ET calculated using the recursive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

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, and r_c = 0.45 s m^{-1}) (fig. 2a). There was some underestimation 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. 2b). 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 overestimation of ET_r at large

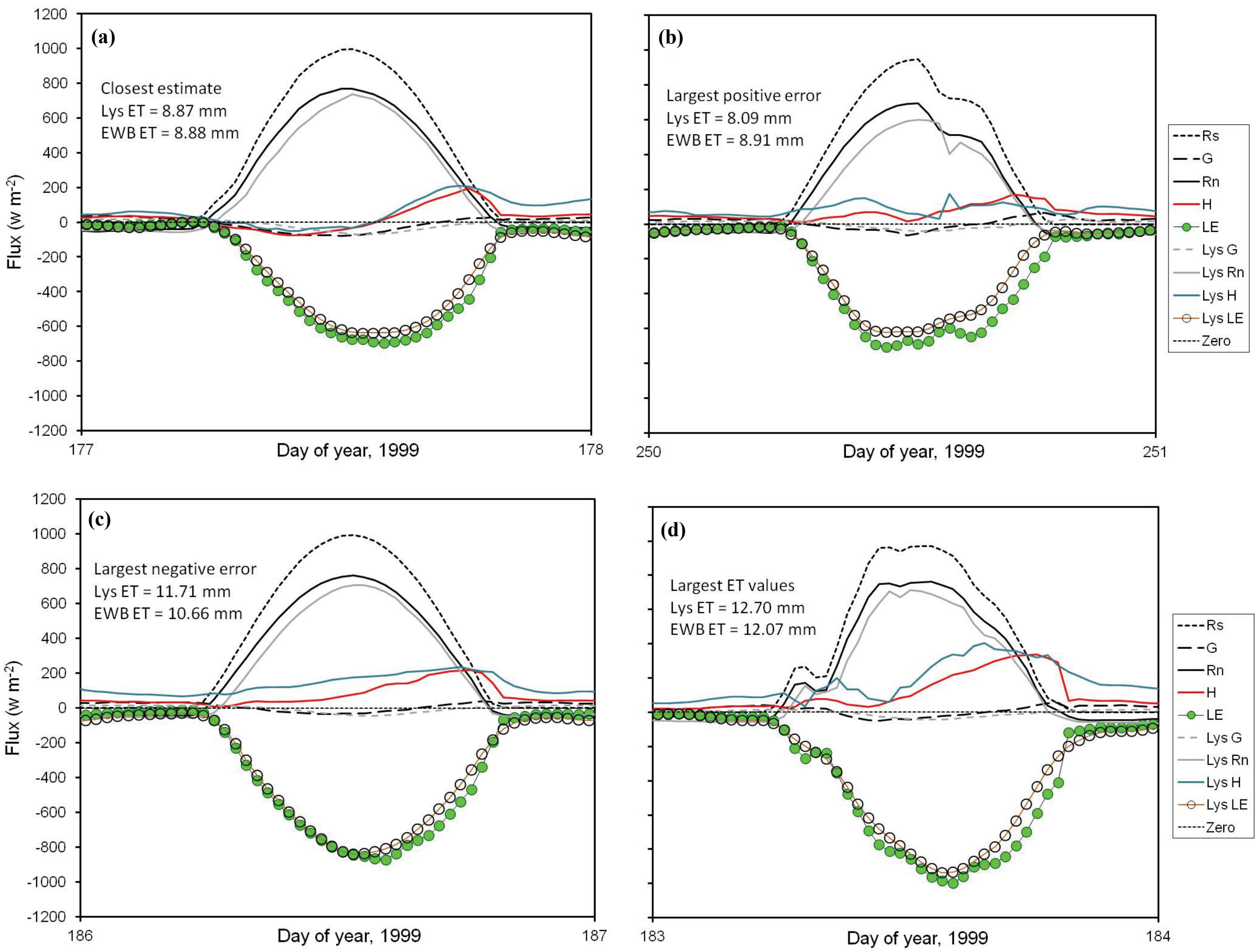

Figure 3. Energy fluxes (W m^{-2}) and daily ET values (mm) as estimated using ENWATBAL (EWB ET; Evett and Lascano, 1993) and measured with a weighing lysimeter (Lys ET) for (a) the day when the 24 h ET estimate most closely matched the lysimeter measurement, (b) the day when ET was overestimated the most, (c) the day when the ET was underestimated the most, and (d) the day when both estimated and measured ET were the largest.

values (ET_r = 1.05 × lysimeter ET + 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):

$$r_c = 0.7657t_h^2 - 20.934t_h + 173.93 \quad (r^2 = 0.80) \qquad (19)$$

Half-hourly fluxes of H and LE and of R_n and G were compared between the ENWATBAL estimates and lysimeter-measured values (H for the lysimeter was computed as the residual of the energy balance equation using measured LE, G, and R_n) (fig. 3). The closest estimate of lysimeter ET was on day of year (DOY) 177, when lysimeter ET was 8.87 mm and ENWATBAL-estimated ET was 8.88 mm (fig. 3a). Lysimeter G and H were well estimated by ENWATBAL during daytime, but R_n was overestimated, and the magnitude of LE was also overestimated (more negative values of LE from ENWATBAL in fig. 3a). After sunset, H was underestimated by up to 100 W m^{-2} by ENWATBAL, and the magnitude of LE was underestimated 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.

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 underestimated H early in the daytime hours and overestimated R_n. Then late in the daytime hours, H was overestimated while R_n estimates matched measurements. Throughout the daytime hours, ENWATBAL overestimated 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 T_a 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 overestimation of ET. Thus, it seems that formulating surface resistance as a function of vapor pressure deficit might improve ET_r estimation.

The largest negative error in estimation by ENWATBAL occurred on DOY 186, when lysimeter-measured ET was 11.71 mm and ENWATBAL-estimated ET 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). Due to mis-estimation of canopy temperature, ENWATBAL underestimated H at night and for most of the

Table 1. Daily mean weather variables, including relative humidity (RH) and total daily solar irradiance (R_s), along with daily values of lysimeter-measured alfalfa evapotranspiration, reference ET estimated using ENWATBAL (RCM ET_r), and ET estimated using the ASCE standardized Penman-Monteith method (ASCE PM ET_r; Allen et al., 2005) for each day of year (DOY). The maximum values are shaded.

DOY	Mean Wind Speed (m s^{-1})	Mean Air Temp. (°C)	Mean RH (%)	Total R_s (MJ m^2)	Lysimeter ET (mm)	RCM ET_r (mm)	ASCE PM ET_r (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

daytime. Low estimates of the magnitude of nighttime LE as compared with lysimeter-measured LE accounted for most of the underestimation of daily ET.

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 underestimated for most of the daytime and nighttime. As was evident for DOY 177 and DOY 186, *H* was particularly underestimated 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.

The idea that surface resistance is variable is not new (e.g., as established for grass by Todorovic, 1999; Lecina et al., 2003; and Allen et al., 2006). Lecina et al. (2003) concluded that substantial improvement resulted from using a variable resistance model (Todorovic, 1999) with hourly data in a semi-arid and windy environment. However, these studies indicate that improvements in daily reference ET estimation using half-hourly or hourly weather data are not large. Affirming this, the generally good agreement between the three methods used herein and the measured alfalfa reference ET indicates that the accuracy gains from adopting a variable surface resistance would not be large. Larger effects would be seen when ET of deficit-irrigated crops is estimated directly using the recursive method or the ENWATBAL model or similar one- or two-layer models.

CONCLUSIONS

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 2005 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 representing daytime surface resistance as a function of vapor pressure deficit might improve ET_r calculation. These conclusions mean that the constant C_d in equation 4 should be a variable. The importance of these conclusions should not be overstated, however, since overall ET estimation was good. Further study is needed to investigate the use of surface resistance formulations that include both vapor pressure deficit and solar irradiance as independent variables.

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