A FIELD TEST OF RECURSIVE CALCULATION OF CROP EVAPOTRANSPIRATION

R. J. Lascano, C. H. M. van Bavel, S. R. Evett

ABSTRACT. *Unlike the Penman and Penman-Monteith methods, recursive calculation of crop evapotranspiration (ET) is a combination method that makes no assumption regarding the temperature and saturation humidity at the evaporating surface. Our objective was to experimentally verify a recursive calculation of crop ET. It was tested on an hourly and daily basis using data from Bushland, Texas, and on a daily basis with data from Tempe, Arizona, both on a well-watered alfalfa crop. In both locations, ET was measured half-hourly with lysimeters accurate to 0.05 mm. In Bushland, hourly amounts of ET were calculated from the hourly weather data using the recursive method with a root mean squared difference (RMSD) of 0.05 mm averaged over four days; and daily ET calculations using daily data for 26 days resulted in an RMSD of 0.75 mm. The sum of 26 daily-calculated values of ET was found to be within 7 mm of the measured amount. In Tempe, daily ET was also calculated with the same recursive formula from daily weather data for a period of 20 days after a flood irrigation that kept the crop well watered. The RMSD of daily ET was 0.8 mm, and the calculated total amount of ET over 20 days was within 2 mm of the measured value. We conclude that an iterative formulation provides good accuracy for calculating ET of well-watered alfalfa and that similar studies with other irrigated crops grown in hot and dry climates are needed.*

***Keywords**. Alfalfa, Canopy resistance, Crop water use, Energy balance, ET estimation methods, Evapotranspiration, Penman-Monteith.*

In 1948, two seminal papers were published that impacted our understanding of evaporation, i.e., Penman (1948) and Thornthwaite (1948). The latter coined the term potential evapotranspiration (ET_p) as the maximum rate of water loss by evaporation from vegetation when a soil has at no time a deficiency of water. Penman (1948) introduced a method to calculate *ET* from open water, bare soil, and grass that was called the combination method because it combined the energy balance and an aerodynamic or diffusion formula to calculate *ET*. The method was made explicit by eliminating the surface temperature from the relevant equations (e.g., Sibbons, 1962), an approach that has since been refined by others (e.g., Paw and Gao, 1988; Milly, 1991). An energy balance solution was proposed independently by Budyko (1951, 1956), who termed the approach the complex method after 1956.

The methods proposed by Penman (1948) and by Budyko (1951, 1956) to calculate *ET* were independent of each other. Moreover, there was a major distinction between them in that the assumption made by Penman (1948) regarding the temperature and the humidity of the evaporating surface was not required with the method proposed by Budyko (1951, 1956), which was an iterative one, consisting of an energy balance equation with two unknowns, *ET* and the surface temperature T_s. Budyko (1951, 1956) used the Goff-Gratch equation (Goff and Gratch, 1945) that relates the saturation humidity at a surface to the temperature at that surface. Starting with an initial value for T_s, the value of both unknowns was found by iteration, resulting in a value of T_s that satisfied the energy balance. An outline of this procedure was given by Budyko (1951, 1956, pp. 162-163) and explained by Sellers (1964, 1965, pp. 168-170). Theories describing the relation between vapor pressure and air temperature (T_a) in relation to the calculation of crop *ET* using explicit combination methods are given by Evett (2002, pp. 157-159) and by Rose (2006, pp. 175-182). Hereafter, we refer to the procedure based on Penman (1948) as the explicit combination method (ECM) and that based on the iterative procedure first suggested by Budyko (1951, 1956) as the recursive combination method (RCM).

The relative error in the evaporation rate calculated from ECM methods is given by Milly (1991). His analysis (see his eq. 30) indicated that the ECM methods can typically underestimate crop *ET* and that the error goes to zero when the latent heat flux is identical to the available energy and there is no sensible heat flux, i.e., $T_a \equiv T_s$. The magnitude of the underestimation of crop *ET* depends on values of weather variables and on values selected for the aerodynamic (r_a) and canopy resistance (r_c). For example, Paw and Gao (1988) and Milly (1991) reported close to 20% underestimation of crop *ET* using ECM.

A comparison of crop *ET* calculated using ECM and RCM is given by Lascano (2006), Lascano and Van Bavel (2007), and more recently by Hay and Irmak (2009). For example,

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Lascano (2006) compared daily values of crop *ET* for a short grass using weather from Lubbock, Texas. The ECM used in this comparison was the grass reference *ET* equation given by Allen et al. (2005). The results from this comparison showed that on days with a high evaporative demand (crop *ET* > 10 mm d^{-1}) the ECM underestimated crop *ET* by as much as 18%. For days with a low evaporative demand (crop *ET* < 4 mm d^{-1}) the underestimation was about 10% (Lascano, 2006). Similar results were given by Lascano and Van Bavel (2007) with a 25% underestimation of potential and crop *ET*, particularly under hot, low humidity, and windy conditions. However, the evaluations of Lascano (2006) and Lascano and Van Bavel (2007) were solely based on calculated values of crop *ET* with no comparison to measured values.

A comparison between daily grass *ET* calculated by ECM and RCM with values measured with a Bowen ratio system are given by Hay and Irmak (2009). They concluded that results of grass *ET* were sensitive to the value chosen for the canopy resistance, r_c. For example, for an equivalent value of r_c, grass *ET* calculated by the ECM was greater than the grass *ET* calculated from the RCM, a result that according to Milly (1991) is not physically correct, i.e., ECM can only underestimate crop *ET*. The best comparison to measured daily values of grass *ET* was obtained when r_c = 40 s m^{-1} for ECM and r_c = 20 s m^{-1} for RCM. Nevertheless, values of crop *ET* obtained with the RCM given by Lascano and Van Bavel (2007), which are based on the iterative computation suggested by Budyko (1951, 1956), need additional evaluation by comparing them to measured values of crop *ET*.

Therefore, the objective of this study was to experimentally verify the RCM proposed by Lascano and Van Bavel (2007). For this purpose, we used a three-month 1999 weather and crop *ET* dataset from Bushland, Texas, and a 20-day 1964 dataset from Tempe, Arizona, both measured over well-watered alfalfa. First, using the Bushland, Texas, weather, we compared hourly and daily values of alfalfa *ET*, measured with a large weighing lysimeter (Marek et al., 1988; Howell et al., 1995), to values calculated using both hourly and daily measured values of air and dewpoint temperature, wind speed, net irradiance, and soil heat flux. Second, using the Tempe, Arizona, weather data, we compared daily values of alfalfa *ET* measured with weighing lysimeters (Van Bavel, 1967) to values also calculated with the RCM.

Materials and Methods

Alfalfa Fields, Experimental Lysimeter Data, and Weather Data

In our calculations, we used weather data from two locations: Bushland, Texas, and Tempe, Arizona. In both locations, alfalfa *ET* was measured with weighing lysimeters on a well-established alfalfa crop and under well watered conditions. In Bushland, Texas, we selected 26 days, between 23 May and 12 September 1999, all after a day of irrigation and determined to be without equipment failure, irrigation, or rainfall and with a range of cloudiness. In Tempe, Arizona, we used 20 consecutive days, 29 May to 17 June 1964, also with no rain or irrigation and clear weather (Van Bavel, 1967). A brief description of the procedures at the two locations follows.

Bushland, Texas

At Bushland, Texas, research was conducted at the USDA-ARS Conservation and Production Research Laboratory (35° 11′ N, 102° 06′ W, 1170 m elev. above MSL) on a Pullman clay loam soil. Alfalfa (*Medicago sativa* L.) variety Pioneer 5454 was seeded at a rate of 28 kg ha^{-1} on 13-14 September 1995, with a grain drill on 0.2 m spacing operated in two overlapping directions to improve plant density. The crop was irrigated and fertilized to produce a well-watered vegetative surface without limitations of fertilizer or other inputs or management (Evett et al., 2000).

The masses of large weighing lysimeters (Dusek et al., 1987) were measured every 6 s, and mean values were recorded every 0.5 h with an accuracy equivalent to 0.05 mm of water depth (Howell et al., 1995). Values of alfalfa *ET* were calculated from the water balance and reported every 0.5 h at the midpoint of the measurement period. On the days reported herein, the water balance components other than *ET* were known to have zero values.

Experimental weather data at Bushland, Texas, consisted of half-hourly values of air (T_a) and dewpoint (T_d) temperature, net (R_n) and incoming shortwave (R_g) irradiance, soil heat flux (G), and wind speed (U_z) on 26 days selected with no rain or irrigation in 1999. These input data were used to calculate hourly and daily values of *ET* using the RCM as given by Lascano and Van Bavel (2007). Weather variables were measured every 6 s and reported as 0.5 h averages. Net irradiance was measured over the lysimeters with net radiometers (model Q*5.5, REBS, Seattle, Wash.), and G was measured in the lysimeters with four heat flux plates (model HFT-1, REBS, Seattle, Wash.) buried 0.05 m below the surface with thermocouples for measurement of soil temperature buried at 0.02 and 0.04 m below the soil surface above each plate. The net radiometers were checked against the sum of the net radiation components as measured by an albedometer (model CM14, Kipp and Zonen, Delft, The Netherlands) and two pyregeometers (model CG2, Kipp and Zonen, Delft, The Netherlands and model PIR, Eppley Laboratories, Inc., Newport, R.I.). Air and dewpoint temperatures and wind speed were measured at a screen height of 2.0 m over a nearby grass field and solar irradiance (R_g) was measured nearby, all using standard procedures described by Evett (2002). Additional input data were the measured alfalfa height (h_c) for the 26 selected days. The average daily T_a in °C, T_d in °C, and U_z in m s^{-1}, and daily totals of R_g in MJ m^{-2}, R_n in MJ m^{-2}, and G in MJ m^{-2}, measured alfalfa *ET* (ET_m, mm d^{-1}) with a lysimeter, and measured h_c in m on 26 days of 1999 in Bushland, Texas, are shown in table 1.

Tempe, Arizona

The alfalfa field located at the U.S. Water Conservation Laboratory (33° 25′ N, 111° 56′ W, 381 m elev. above MSL) in Tempe, Arizona, was ~0.8 ha in size and was flood irrigated on 28 May 1964. The crop was trimmed to 0.2 m height on 4 June 1964, leaving a well-developed canopy (Van Bavel, 1967). For daily calculations of alfalfa *ET* in Tempe, Arizona, we used the daily weather data from 29 May to 17 June 1964 given in table 1 in Van Bavel (1967). Missing daily values of vapor pressure for two days and wind speed for three days were substituted by interpolation using the average of the previous three days. Hourly alfalfa *ET* rates were measured in triplicate with weighing lysimeters, and half-hourly values of

Table 1. Daily average air (T_a) and dewpoint (T_d) temperature, wind speed (U_z), and daily total shortwave (R_g) and net (R_n) irradiance, and soil heat flux (G) for 26 days in Bushland, Texas. Also given are the daily measured values of ET (ET_m) and crop height (h_c).

DOY (1999)	T_a (°C)	T_d (°C)	U_z (m s^{-1})	R_g (MJ m^{-2})	R_n (MJ m^{-2})	G (MJ m^{-2})	ET_m (mm d^{-1})	h_c (m)
143	17.71	11.88	3.73	24.10	12.94	0.14	5.72	0.52
148	14.79	11.33	1.89	24.27	13.67	0.19	4.59	0.60
150	20.41	12.48	3.48	30.90	17.64	0.70	9.27	0.64
151	20.93	11.92	2.21	25.77	13.96	0.59	6.91	0.65
152	19.19	7.60	3.22	31.96	17.23	0.23	8.11	0.67
167	15.84	10.78	4.69	29.12	18.04	0.07	6.19	0.29
169	20.53	13.85	5.56	23.21	13.55	0.44	7.37	0.33
170	21.91	13.20	2.89	23.20	12.77	0.69	6.60	0.35
173	22.08	17.77	5.06	29.88	18.53	1.07	7.85	0.41
177	24.64	18.13	4.45	30.19	17.88	1.01	8.82	0.49
178	27.58	16.00	4.23	28.95	16.86	0.91	10.78	0.51
180	25.04	16.26	4.62	30.61	18.97	0.68	11.25	0.55
182	24.15	18.04	4.60	29.32	17.14	0.39	9.32	0.59
183	26.43	16.88	6.45	28.53	16.36	0.31	12.64	0.61
185	24.28	16.38	6.60	30.06	17.39	0.23	11.05	0.65
186	24.47	15.59	5.49	30.51	17.78	0.25	11.71	0.67
206	25.64	14.04	3.68	28.71	16.51	0.04	10.32	0.56
212	25.24	15.00	4.23	27.00	15.93	0.16	8.91	0.67
213	21.30	16.02	3.50	24.29	13.20	-0.11	6.26	0.67
219	23.94	17.51	2.75	27.66	16.79	0.55	7.35	0.64
223	24.29	15.88	3.86	26.02	15.11	0.01	8.92	0.56
248	19.90	13.84	3.24	23.95	12.04	-0.43	5.26	0.54
251	18.57	13.37	4.78	8.61	3.82	-1.11	3.47	0.59
253	22.97	11.68	5.32	23.34	12.13	-0.10	9.75	0.61
254	21.87	13.18	3.04	23.11	11.34	-0.04	6.01	0.62
255	15.25	10.70	4.81	12.44	5.43	-1.72	3.94	0.63

R_n, T_a, T_d, and U_z were recorded (Fritschen and Van Bavel, 1963). Soil heat flux was not measured, and in our calculations of daily ET we assumed a daily value of G = +0.2 MJ m^{-2} based on measurements at Bushland, Texas. Values of daily measured alfalfa ET and crop height were taken from figures 2 and 3, respectively, given by Van Bavel (1967).

Procedures

In this section, we describe the RCM used to calculate crop ET given by Lascano and Van Bavel (2006) and based on the iterative computation suggested by Budyko (1951, 1956). The iterative procedure can be solved using a spreadsheet program such as Excel (v. 2007, Microsoft Corp., Redmond, Wash.) using the Solver (add-in feature) or the mathematical software Mathcad (v. 14, Parametric Technology Corp., Needham, Mass.). We have compared calculations of crop ET obtained with Excel and Mathcad and obtained identical results (Lascano and Van Bavel, 2007).

The calculation of crop ET using an RCM requires as input daily or sub-daily (e.g., hourly) values of T_a, T_d, U_z, and R_n and of G. Other crop-related input parameters are the crop height (h_c, m) and canopy resistance (r_c, s m^{-1}). The first step is to calculate the aerodynamic resistance (r_a, s m^{-1}), which is a function of wind speed and h_c. Second, the surface temperature (T_s, °C) that satisfies the energy balance is calculated. This value is found by iteration, thus the nature of the recursive combination method. Third, since the sensible heat flux (H, W m^{-2}) is explicitly calculated using the final value of T_s, H is used along with the measured values of R_n and G to calculate the crop's latent heat flux ET from the surface energy balance.

Calculation of Crop *ET*

The surface energy balance is given by:

$$R_n + G + \lambda\, ET + H = 0 \quad (1)$$

where R_n is net radiation, G is soil heat flux, λET is the latent heat flux (product of latent heat of vaporization λ and the evaporative flux from the soil and crop ET), and H is the sensible heat flux. All terms are positive when the flux is toward the surface and in W m^{-2}. The value of λ (J kg^{-1}) was calculated as a function of T_a (Harrison, 1965) as:

$$\lambda = 2.501 \times 10^6 - 2.361 \times 10^3\, T_a \quad (2)$$

The expression to solve for surface temperature (T_s, °C) written in Mathcad syntax is given by:

$$T_s = root\left\{\left[R_n + G + \frac{(T_a - T_s)\times\rho_a\times C_p}{r_a} - \frac{1.323\times\dfrac{\exp\left(17.269\times\dfrac{T_s}{T_s+237.0}\right)-hum}{T_s+273.2}}{r_a+r_c}\times\lambda\right]\times\frac{r_a}{C_p\times\rho_a}, T_s\right\} \quad (3)$$

where *root* is the Mathcad built-in function to solve for the value of T_s, C_p is the specific air heat capacity (J kg^{-1} °C^{-1}), *hum* is the ambient air density (kg m^{-3}), r_a is the aerodynamic resistance (s m^{-1}), r_c is the canopy resistance (s m^{-1}), ρ_a is the air density (kg m^{-3}), and λ is the latent heat of vaporization calculated with equation 2. The value of r_c used in our calculations was based on the iterative procedure given by Lascano and Van Bavel (2007) and a brief description follows.

An hourly value of r_c was calculated for each day of the Bushland, Texas, weather data set shown in table 1. For each day of the Bushland, Texas, weather dataset, the hourly alfalfa energy balance was solved from the pertinent hourly weather input data, i.e., T_a, T_d, U_z, and R_n and from the vertical G using the RCM as given by Lascano and Van Bavel (2007) for values of r_c ranging from 10 to 70 s m^{-1} in 5 s m^{-1} increments, resulting in a value of crop *ET* for each hour and for each value of r_c. The r_c values from 10 to 70 s m^{-1} were selected as they represent the expected range for a well-watered alfalfa crop (Allen et al., 2005). In this calculation, the energy balance equation and Murray's equation (Murray, 1967) for the saturation vapor pressure were combined into a single implicit expression that must equal zero and that was solved by iteration. For each value of r_c, the unknown was the surface temperature (T_s), and iterations began with an initial value of T_s = 10.0°C. For each value of r_c, the solution to equation 3 yielded implicitly a value of crop *ET*, as we will show later, resulting in a table or a graph of calculated values of *ET* as a function of r_c. The value of alfalfa ET_m measured with the lysimeter was then used to find the value of r_c for the corresponding hourly weather data from an automatically produced graph, showing the relation between calculated *ET* and r_c.

Once the value of T_s was known, both *H* and crop *ET* were explicitly calculated. The sensible heat flux (*H*) was calculated as:

$$H = \frac{\rho_a \times C_p \times (T_s - T_a)}{r_a} \tag{4}$$

which is implicit in equation 3, and the crop *ET* (mm h^{-1}) was calculated by rearranging equation 1:

$$ET = \frac{R_n + H + G}{\lambda} \times 3600 \tag{5}$$

In equation 5, we assumed a density of water equal to 1000 kg m^{-3}, and 3600 converts *ET* from m s^{-1} to mm h^{-1}. Note also that, in equation 5, *H* is the only calculated energy balance flux value, as R_n and *G* were both measured at Bushland, Texas, and we assumed *G* = +0.2 MJ m^{-2} d^{-1} in Tempe, Arizona, where R_n was also measured.

Calculation of Aerodynamic Resistance (r_a)

The transfer of sensible heat flux (*H*, eq. 4) is proportional to the aerodynamic resistance (r_a, s m^{-1}), and the transfer of latent heat flux (λET) is proportional to the sum of the r_a and the r_c. The aerodynamic resistance (r_a) for neutral atmospheric conditions was calculated as given by Allen et al. (1989) and used by others, e.g., Evett (2002):

$$r_a = \frac{\ln\left[\frac{(z_w - d)}{z_{om}}\right] \ln\left[\frac{(z_r - d)}{z_{ov}}\right]}{k^2 U_z} \tag{6}$$

where z_w is the height of wind speed measurement (m), z_{om} is the momentum roughness length (m), z_r is the measurement height for humidity (m), z_{ov} is the vapor roughness length (m), *k* is von Karman's constant (*k* = 0.41), *d* is the zero-plane displacement height (m), and U_z is the wind speed (m s^{-1}) at screen height *z* (m). In equation 6, the values of z_w, z_r, and *z* were 2.0 m. A stability correction factor could be introduced to equation 6, as done by others (e.g., Van Zyl and De Jager, 1987; Ottoni et al., 1992; Mölder and Lindroth, 2001), but this is not commonly used in Penman-Monteith formulations and thus was not considered (Evett, 2002).

The aerodynamic crop parameters d, z_{om}, and z_{ov} were empirically estimated, as given by Evett (2002), as follows:

$$d = \frac{2}{3} h_c \tag{7}$$

$$z_{om} = 0.123 h_c \tag{8}$$

$$z_{ov} = 0.1 z_{om} \tag{9}$$

where h_c is the measured crop height (m).

Comparison of Measured and Calculated Values of *ET*

A problem when comparing measured and calculated values of alfalfa *ET* is to use an independent data set to derive values of canopy resistance (r_c) that are subsequently used to calculate and then compare to both hourly and daily values of alfalfa *ET* for a well-watered alfalfa crop. In our comparison of measured and calculated hourly values of alfalfa *ET* for Bushland, Texas, we used calculated hourly canopy resistance (r_c) values from DOY 151 and assumed that these values were applicable to other days where the crop was also well watered. In our case, DOY 151 was randomly selected from the 26 days of weather (table 1) to calculate hourly values of r_c, and the four days (DOY 150, 185, 251, and 253) used in the hourly comparisons were selected as examples to give a range of daily shortwave irradiance, from a low of 8.61 MJ m^{-2} d^{-1} for DOY 251 to a high of 30.90 MJ m^{-2} d^{-1} for DOY 150. Values of r_c were only calculated during daylight hours when R_n > 0 W m^{-2}. Furthermore, in our comparison of measured and daily values of alfalfa *ET* for Bushland, Texas, and for Tempe, Arizona, we used the average hourly r_c calculated from the Bushland 26-day dataset. The alfalfa crop at both locations was considered to be under well-watered conditions.

The hourly value of *ET* for DOY 150, 185, 251, and 253 at Bushland, Texas, was calculated using the hourly calculated values of r_c for DOY 151. For this purpose, a second-order polynomial was fitted to the calculated values of r_c vs. hour of the day for DOY 151, and the resulting equation was used to estimate both day and nighttime hourly values of r_c, which were then used to calculate hourly *ET* using RCM. In addition, the daily values of *ET* for the 26 days were calculated using a constant value of r_c, which was the calculated average of r_c for the 26 days. In Tempe, Arizona, following a flood irrigation, 20 daily values of alfalfa *ET* were calculated using the value of r_c derived from well-watered conditions in Bushland, Texas.

Calculated hourly and daily values of *ET* from Bushland and Tempe, both obtained using the RCM, were compared to values measured with lysimeters using linear regression analysis and root mean squared differences (RMSD) following Kobayashi and Salam (2000). In the linear regression analy–

sis between calculated (x) and measured (y) hourly and daily values of ET, we evaluated if the slope was significantly different from unity and if the intercept was significantly different from zero. The RMSD was calculated as follows:

$$\text{RMSD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_1)^2} \quad (10)$$

where n is the number of comparisons between calculated (x_i) and measured (y_i) values. An RMSD value of 0 indicates that x and y values are equal. The RMSD is a measure of the deviation of calculated values of ET from measured values.

Results and Discussion

Results presented are based on weather data obtained on 26 days of the total 122 in the months of May through August of 1999 at Bushland, Texas (table 1) and on 20 consecutive days, 29 May to 17 June 1964, at Tempe, Arizona (Van Bavel, 1967). The Bushland data set was used to compare measured hourly and daily vales of crop ET to values calculated with the RCM. The weather data set from Tempe, Arizona, were used as an additional example of the application of the RCM to calculate the daily water use by a well-watered alfalfa crop.

Canopy Resistance (r_c)

Hourly Values

The weather data at 1400 h for DOY 150, 185, 251, and 253, 1999, Bushland, Texas, were used as examples to illustrate the hourly determination of r_c (table 2, fig. 1). For DOY 150 at 1400 h, the measured ET_m was 1.07 mm, which intersected the $ET_c = f(r_c)$ line at r_c = 32.1 s m^{-1}. Corresponding values at 1400 h for DOY 185 were ET_m = 1.05 mm, giving r_c = 34.2 s m^{-1}; for DOY 251, ET_m = 0.28 mm, giving r_c =

Table 2. Environmental input for four days of year (DOY) in 1999 used to calculate alfalfa canopy resistance (r_c) at 1400 h using evapotranspiration measured (ET_m) with a lysimeter in Bushland, Texas. The weather variables, all measured at a screen height of 2.0 m, are air (T_a) and dewpoint (T_d) temperature, wind speed (U_z), shortwave (R_g) and net irradiance (R_n), and soil heat flux (G). Also given is the crop height (h_c) and canopy resistance (r_c).

DOY (1999)	T_a (°C)	T_d (°C)	U_z (m s^{-1})	R_g (W m^{-2})	R_n (W m^{-2})	G (W m^{-2})	h_c (m)	ET_m (mm)	r_c (s m^{-1})
150	26.4	12.3	5.9	992.5	660.2	47.5	0.64	1.07	32.1
185	27.7	16.5	6.9	969.6	690.2	44.4	0.65	1.05	34.2
251	18.4	13.1	4.9	274.6	167.3	-7.1	0.59	0.28	32.0
253	28.9	10.4	7.1	889.7	572.8	25.9	0.61	1.16	35.1

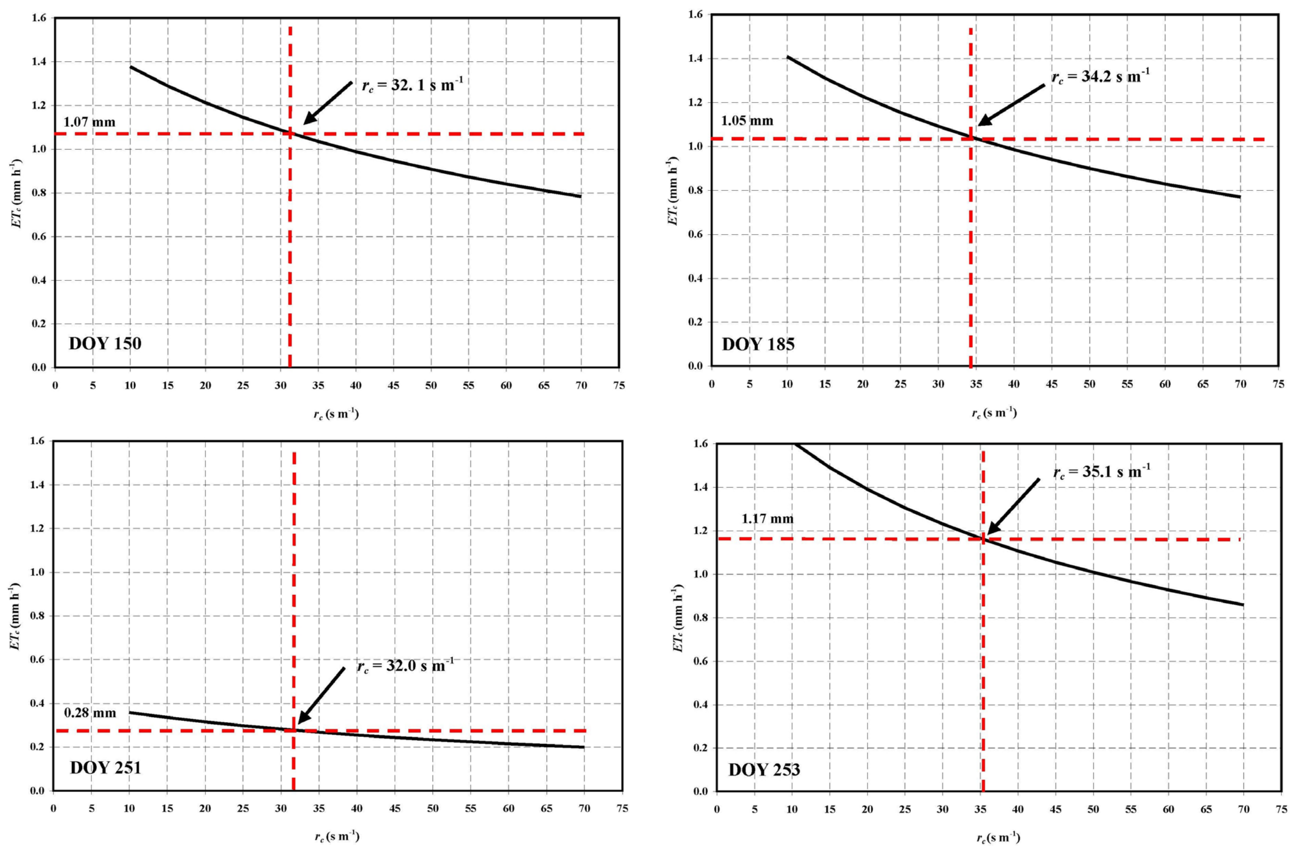

Figure 1. Values of canopy resistance (r_c) at 1400 h on the four selected days in 1999 for the alfalfa crop from the measured value of ET over 1 h. On DOY 150, the ET measured (ET_m) with a lysimeter was 1.07 mm, which corresponds to r_c = 32.1 s m^{-1}; on DOY 185, ET_m was 1.05 mm, which corresponds to r_c = 34.2 s m^{-1}; on DOY 251, ET_m was 0.28 mm, which corresponds to r_c = 32.0 s m^{-1}; and on DOY 253, ET_m = 1.17 mm, which corresponds to r_c = 35.1 s m^{-1}.

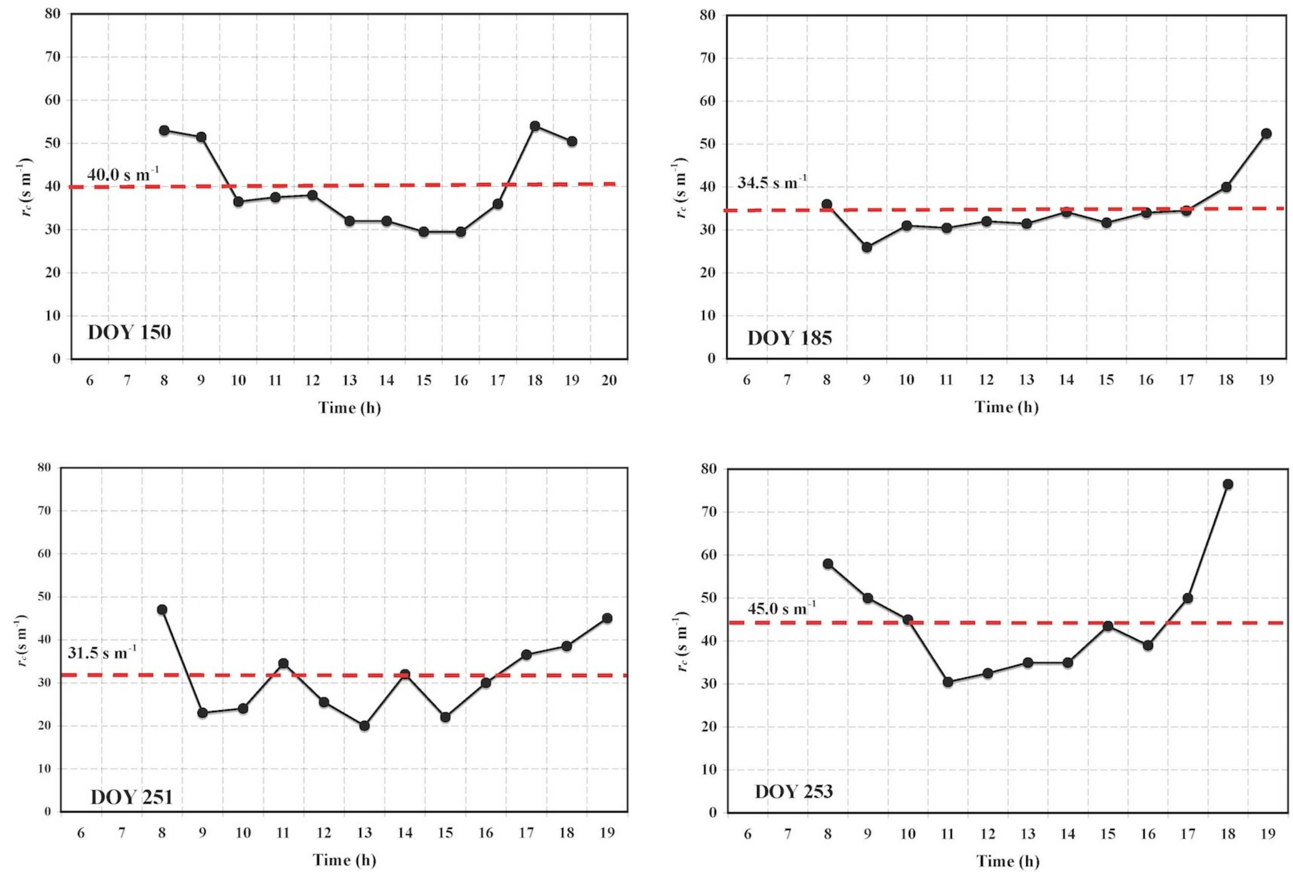

Figure 2. Hourly calculated values of alfalfa canopy resistance (r_c) for four days in Bushland, Texas. The values of r_c were obtained using the graphical interpolation method shown in figure 1, and the average r_c for each day is indicated by the dashed line. On DOY 150 the daily average r_c = 40.0 s m^{-1}; on DOY 185 the daily average r_c = 34.5 s m^{-1}; on DOY 251 the daily average r_c = 31.5 s m^{-1}; and on DOY 253 the daily average r_c = 45.0 s m^{-1}.

32.0 s m^{-1}; and for DOY 253, ET_m = 1.17 mm, giving r_c = 35.1 s m^{-1}.

The hourly calculation of r_c using the procedure shown in figure 1, for daylight hours when $R_n > 0$ W m^{-2}, was done for DOY 150, 185, 251, and 253 and is shown in figure 2. These results showed that the hourly value of r_c throughout the day was relatively constant, particularly during the middle of the day (1000-1600 h) when the stomata presumably were fully open (fig. 2). On DOY 150, the average hourly ± standard deviation r_c was 40.0 ±9.5 s m^{-1}, n = 12; on DOY 185 the average r_c was 34.5 ±6.6 s m^{-1}, n = 12; on DOY 251 the average r_c = 31.5 ±9.0 s m^{-1}, n = 12; and on DOY 253 the average r_c was 45.0 ±13.5 s m^{-1}, n = 11. The increase of resistance near sunrise and sunset is in line with the expected sunlight-dependent stomatal opening (e.g., Van Bavel and Ehrler, 1968; Turner, 1970; Bates and Hall, 1982; Knapp and Smith, 1990).

Daily Values

The daily averages and standard deviations of alfalfa canopy resistance (r_c) for the 26 days during the 1999 growing season in Bushland, Texas, indicated that the daily average value was not constant throughout the growing season (fig. 3). Daily canopy resistance (r_c) increased from about 35 s m^{-1} on DOY 143 to 60 s m^{-1} on DOY 170, gradually decreased to 40 s m^{-1} on DOY 186, and thereafter remained constant at around 45 s m^{-1} until DOY 248, with no pattern on the last four days. It is beyond the scope of this article to explain why daily r_c values varied so much, but we expect to explore this more fully in a subsequent article. The daily average ± standard deviation r_c was 45.6 ±11.3 s m^{-1}.

Values of r_c for alfalfa obtained by different methods are given by others (Allen et al., 1989; McGinn and King, 1990; Saugier and Katerji, 1991). For example, alfalfa r_c derived from measurements of stomatal conductances on the two sides of the leaf yielded a value of 22 s m^{-1} (Saugier and Katerji, 1991). Daytime values of r_c for unirrigated alfalfa, calculated from the Penman-Monteith equation, showed that r_c varied from a low of 10 s m^{-1} to a high of 60 s m^{-1} with an average of 32.5 s m^{-1} and standard error of 1.24 for a seven-

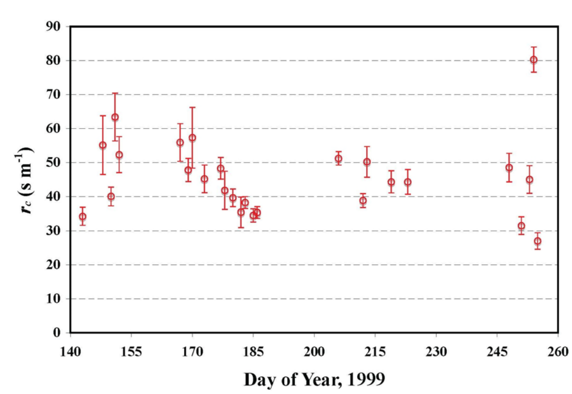

Figure 3. Daily average ± standard deviation (SD) of calculated hourly values of alfalfa canopy resistance (r_c) for 26 days of the 1999-growing season in Bushland, Texas. The average daily ±SD of r_c = 45.6 ± 11.3 s m^{-1}.

week period in Ontario, Canada (McGinn and King, 1990). Values of r_c given by Allen et al. (1989) to calculate a reference alfalfa ET using a Penman-Monteith type equation were r_c = 45 s m^{-1} when using daily weather input, r_c = 30 s m^{-1} when using hourly weather input, and r_c = 200 s m^{-1} for nighttime conditions. These values are numerically similar to the values of r_c that we report for a well-watered crop in a semiarid climate for hourly, daily, and seasonal time periods; however, our values were obtained using an RCM whereas all values obtained by others were calculated with an ECM.

Crop Evapotranspiration: Measured vs. Calculated *Hourly Values*

Comparisons of hourly calculated (ET_c, mm) and measured evapotranspiration (ET_m, mm) values were made for the four selected days (DOY 150, 185, 251, and 253) in Bushland, Texas. In these calculations, we used hourly values of r_c from a different day, i.e., DOY 151, obtained as follows. Hourly values of r_c, when $R_n > 0$ W m^{-2} (800-1900 h) for DOY 151, were fitted with a second-order polynomial relating r_c to time of day in hours. The resulting equation, $r_c = 0.7657 \times \text{time}^2 - 20.934 \times \text{time} + 173.93$ ($R^2 = 0.80$), was used to calculate 24 h values of r_c and used in the subsequent calculations of hourly ET_c for the four selected DOY. Nighttime calculated values of r_c ranged from 60 to 160 s m^{-1}, daylight average ±SD was r_c = 38.0 ±8.0 s m^{-1}, and the diurnal pattern of r_c, obtained with the fitted equation, follows the trends reported for several crops, e.g., grass (Lecina et al., 2003), corn (Irmak et al., 2008), and rice (Maruyama and Kuwagata, 2008).

Table 3. Comparison of the sum of the hourly values of crop *ET* measured with a lysimeter and calculated with RCM for four days in Bushland, Texas. The hourly comparison of *ET* for the four days is shown in figure 4. The root mean squared differences (RMSD) between calculated and measured values are also given.

Day of Year (1999)	Daily *ET* (mm) Calculated	Daily *ET* (mm) Measured	RMSD (mm)
150	9.1	9.3	0.02
185	10.6	11.1	0.04
251	3.6	3.5	0.03
253	10.5	9.7	0.09

Calculated and measured hourly values of ET for DOY 150, 185, 251, and 253 at Bushland, Texas, are shown in figure 4, and a summary of the daily totals of hourly values of ET measured with a lysimeter and calculated with RCM is given in table 3. For the four days, the RMSD of the daily ET was <0.1 mm. A linear regression between hourly calculated (ET_c) and hourly measured (ET_m) values of ET for the values shown in figure 4 gave $ET_c = 1.008\ ET_m - 0.002$ and $r^2 = 0.98$. The slope of the linear regression was not significantly different from 1.0, and the intercept was not significantly different from 0.0. The low values of RMSD, which averaged 0.05 mm for the 48 hourly values of E shown in figure 4, and the regression analysis between hourly ET_m and ET_c, suggest that calculated hourly values of ET for a well-watered alfalfa crop can be accurately estimated using hourly calculated values of r_c (fig. 4) obtained using RCM on a different day when the crop is well watered.

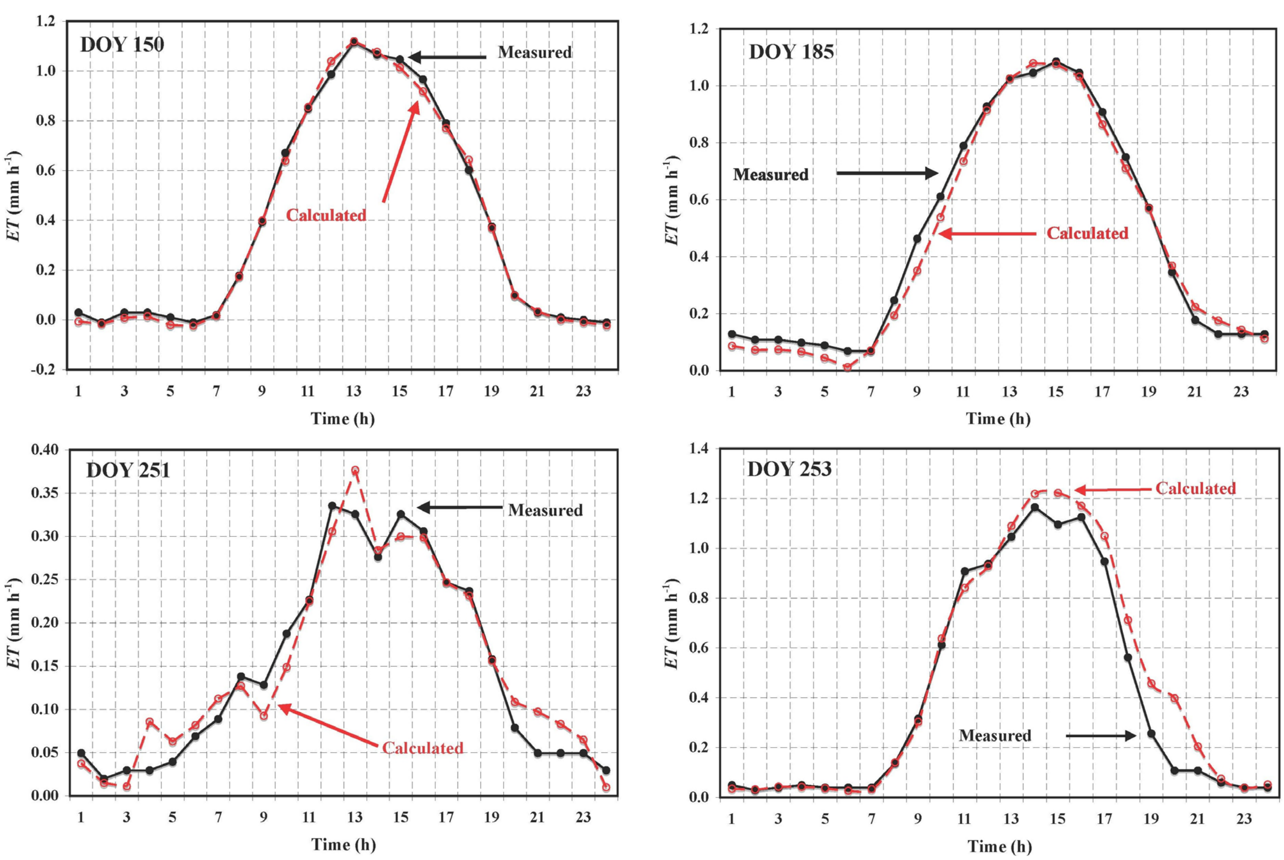

Figure 4. Hourly measured (black circles) and calculated (open circles) values of alfalfa-evapotranspiration (*ET*) for four days in Bushland, Texas. The calculated hourly values of *ET* were obtained with an RCM and using the hourly values of canopy resistance (r_c) for DOY 151.

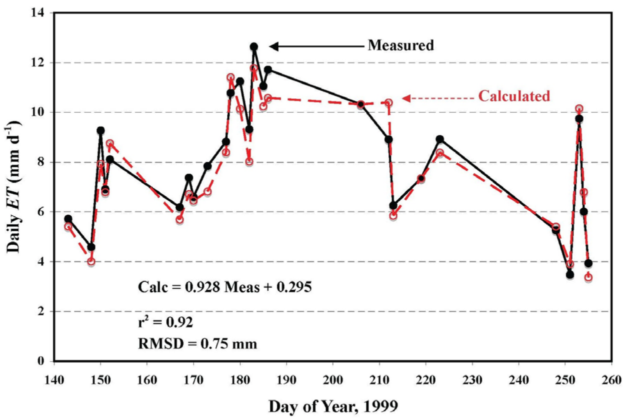

Figure 5. Daily measured (black circles) and calculated (open circles) values of alfalfa-evapotranspiration (*ET*) for 26 days in Bushland, Texas. Calculated values of *ET* were obtained with an RCM and assuming a constant value of canopy resistance (r_c) of 45.6 s m^{-1} for each day and measured values of *ET* were obtained with a lysimeter. The linear regression equation between calculated and measured values of daily *ET*, r^2 and RMSD is shown.

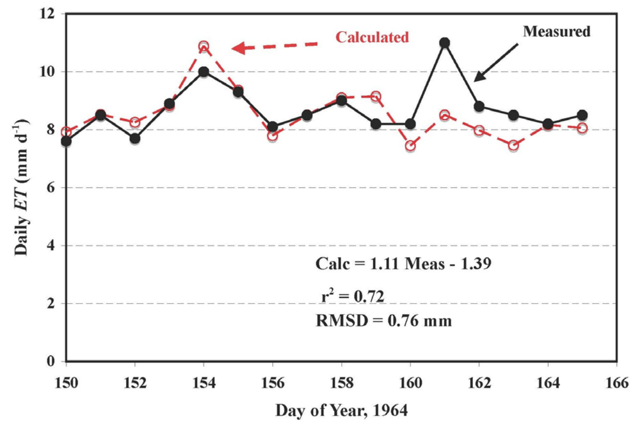

Figure 6. Daily measured (black circles) and calculated (open circles) values of alfalfa-evapotranspiration (*ET*) for 20 days in Tempe, Arizona (Van Bavel, 1967). Calculated values of *ET* were obtained with an RCM and assuming a constant value of canopy resistance r_c = 45.6 s m^{-1}. The linear regression equation between calculated and measured values of daily *ET*, r^2 and RMSD is shown.

Daily Values

A comparison of daily calculated and measured values of *ET* for the 26 days of the 1999 growing season in Bushland, Texas, is shown in figure 5. The daily calculated values of ET_c were obtained assuming a constant r_c = 45.6 s m^{-1} for each DOY, which corresponds to the daily average shown in figure 3. We did not use $r_c = f$(time) because the lack of hourly data from the Tempe site precluded its use for that comparison, and we wanted to use the same r_c for both the Bushland and Tempe daily comparisons of calculated vs. measured *ET*. A linear regression between daily calculated (ET_c) and daily measured (ET_m) values of *ET* for the values shown in figure 5 gave $ET_c = 0.928\ ET_m + 0.295$, r^2 = 0.92 and RMSD = 0.75 mm. The slope was not significantly different from 1.0, and the intercept was not significantly different from 0.0. The RMSD suggests that the RCM was accurate to 0.8 mm in this case. The sum of the daily *ET* over the 26 days of 1999 was 208 mm for measured values and 201 mm for calculated values.

Using the meteorological weather data for 20 days measured over the irrigated alfalfa crop in Tempe, Arizona (Van Bavel, 1967), we calculated the daily alfalfa *ET* assuming r_c = 45.6 s m^{-1} for the first 20 days, i.e., well-watered conditions. Thereafter, the value of r_c increased steeply over the remaining 11 days, attaining a value of 1500 s m^{-1} at the end of the 31st day (Van Bavel, 1967). These 11 days were not used in our analysis since the alfalfa was considered not well watered. Linear regression was used to compare daily *ET* calculated (ET_c) using our RCM with measured (ET_m) values (fig. 6), yielding $ET_m = 1.11\ ET_c - 1.39$, r^2 = 0.72, andRMSD = 0.76 mm. The slope of the linear regression was not significantly different from 1.0, and the intercept was not significantly different from 0.0. On DOY 161, the calculated value of *ET* was underestimated by 2.5 mm compared to the measured value, probably due to advective conditions in the arid climate of Tempe, Arizona, which is not uncommon in dry areas (Tolk et al., 2006). The accumulated daily *ET* was 174 mm for measured values and 176 mm for the 20 daily values calculated using the RCM. The RMSD suggest that RCM was accurate within 0.8 mm for the Tempe, Arizona, data.

Our results show that for any given day the value of r_c for a well-watered alfalfa crop during daylight hours was relatively constant except near sunrise and sunset (fig. 2); however, the daily average r_c did change during the growing season (fig. 3). Nevertheless, calculated values of daily alfalfa *ET* obtained assuming a constant r_c = 45.6 s m^{-1}, i.e., the average for the 26 days, yielded values of daily *ET* that were essentially equal to the daily measured values obtained with large weighing lysimeters at two locations (figs. 5 and 6). This result is of practical significance as it suggests that the daily loss of water from a well-watered crop can be calculated when using a constant value of canopy resistance obtained using the iterative procedure given by Lascano and Van Bavel (2007).

A summary of our results comparing calculated to measured daily values of crop *ET* for both Bushland, Texas, and Tempe, Arizona, is shown in table 4. The cumulative calculated daily *ET* obtained with RCM was within 7 mm (3%) at Bushland and within 2 mm (1%) at Tempe. The RMSD, at both locations, was within 0.8 mm.

Table 4. Comparison of the cumulative crop *ET* from daily values measured with a lysimeter and calculated with RCM for 26 days in Bushland, Texas, and 20 days in Tempe, Arizona. The daily comparison of *ET* for the two locations is shown in figures 5 and 6, respectively. The root mean squared differences (RMSD) between calculated and measured values are also given.

	Cumulative *ET* (mm)			
Location	Calculated	Measured	No. of Days	RMSD (mm)
Bushland	201	208	26	0.75
Tempe	176	174	20	0.76

Summary and Conclusions

Lascano and Van Bavel (2007) demonstrated that the explicit Penman-Monteith equation to calculate evapotranspiration could result in significant errors at high ambient air temperatures and low humidities and that these errors could be avoided by using a recursive combination method (RCM). Both methods require the value of the surface (canopy) resistance to diffusive flow of water vapor from the leaf canopy. The surface resistance can be obtained in an RCM by a graphical method based on measurement of *ET* with weighing lysimeters and an iterative equation for the surface energy balance, as proposed by Lascano and Van Bavel (2007). To prove its accuracy, hourly and daily values of canopy resistance were used to calculate hourly and daily values of *ET*, and these values were compared to measured values of *ET* obtained with a large weighing lysimeter for 26 days from May to August 1999 on a well-watered alfalfa crop in Bushland, Texas. This comparison showed that the calculated total values of *ET*, both hourly and over the summer season, obtained with the recursive combination method were accurate to within 0.8 mm (RMSD). In addition, daily values of *ET* for a well-watered alfalfa crop at Tempe, Arizona, calculated with the RCM were compared to *ET* values measured by weighing lysimetry. This comparison showed that the calculated total values of *ET* were accurate within 0.8 mm (RMSD).

Using modern computing equipment, the RCM does not require appreciably more calculating effort than the traditional ECM. In the RCM, assumptions of a linear relation between the saturation vapor pressure and air temperature are avoided by an iterative calculation of the surface temperature that satisfies the energy balance of the crop. We conclude that the RCM is sufficiently accurate to be used to calculate hourly, daily, and seasonal *ET* from irrigated crops once values of r_c are established for each crop. To the extent that the r_c values are crop and variety specific rather than climate specific, we conjecture that the RCM method will suffer less accuracy loss when applied in different climates than does the traditional Penman-Monteith ECM when crop coefficients are transferred without change over climatic zones, which has proven to be problematic (e.g., Evett et al., 2009).

References

Allen, R. G., M. E. Jensen, J. L. Wright, and R. D. Burman. 1989. Operational estimates of reference evapotranspiration. *Agron. J.* 81(4): 650-662.

Allen, R. G., I. A. Walter, R. Elliott, T. Howell, D. Itenfisu, and M. Jensen. 2005. The ASCE standardized reference evapotranspiration equation. Prepared by Task Committee on Standardization of Reference Evapotranspiration. Reston, Va.: ASCE Environmental and Water Resources Institute. Available at: www.kimberly.uidaho.edu/water/asceewri/ascestzdetmain 2005.pdf.

Bates, L. M., and E. A. Hall. 1982. Diurnal and seasonal responses of stomatal conductance for cowpea plants subjected to different levels of environmental drought. *Oecologia* 54(3): 304-308.

Budyko, M. I. 1951. The effect of ameliorative measures on evaporation. Izvestiia of the Academy of Sciences S.S.S.R., *Ser Geograficheskaia* 1: 16-35 (cited from Milly, 1991, and Sibbons, 1962).

Budyko, M. I. 1956. *The Heat Balance of the Earth's Surface.* (English translation, N. A. Stepanova, Office of Technical Services, PB 131692, U.S. Department of Commerce, Washington, D.C., 1958).

Dusek, D. A., T. A. Howell, A. D. Schneider, and K. S. Copeland. 1987. Bushland weighing lysimeters data acquisition systems for evapotranspiration research. ASAE Paper No. 872506. St. Joseph, Mich.: ASAE.

Evett, S. R. 2002. Chapter 5: Water and energy balances at soil-plant-atmosphere interfaces. In *Soil Physics Companion*, 127-188. A. W. Warrick, ed. Boca Raton, Fla.: CRC Press.

Evett, S. R., T. A. Howell, R. W. Todd, A. D. Schneider, and J. A. Tolk. 2000. Alfalfa reference ET measurement and prediction. In *Proc. 4th Decennial National Irrigation Symp.*,266-272. R. G. Evans, B. L. Benham, and T. P. Trooien, eds. St. Joseph, Mich.: ASAE.

Evett, S. R., N. T. Mazahrih, M. A. Jitan, M. H. Sawalha, P. D. Colaizzi, and J. E. Ayars. 2009. A weighing lysimeter for crop water use determination in the Jordan Valley, Jordan. *Trans ASABE* 52(1): 155-169.

Fritschen, L. J., and C. H. M. van Bavel. 1963. Micrometeorological data handling system. *J. Appl. Meteorol*. 2(1): 151-155.

Goff, J. A., and S. Gratch. 1945. Thermodynamic properties of moist air. *Trans. American Soc. Heating and Ventilating Eng.* 51: 125-164.

Harrison, L. P. 1965. Fundamental concepts and definitions relating to humidity. In *Humidity and Moisture*, vol. 3: 3-69. A. Wexler, ed. New York, N.Y.: Reinhold.

Hay, C. H., and S. Irmak. 2009. Recursive and explicit combination methods for calculating reference evapotranspiration. In *Proc. World Environ. and Water Resources Congress 2009: Great Rivers. ASCE Conf. Proc.* Reston, Va.: ASCE.

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.

Irmak, S., D. Mutiibwa, A. Irmak, T. J. Arkebauer, A. Weiss, D. L. Martin, and D. E. Eisenhauer. 2008. On the scaling up leaf stomatal resistance to canopy resistance using photosynthetic photon flux density. *Agric. Forest Meteorol.* 148(6-7): 1034-1044.

Knapp, A. K., and W. K. Smith. 1990. Stomatal and photosynthetic responses to variable sunlight. *Physiologia Plantarum* 78(1): 160-165.

Kobayashi, K., and M. U. Salam. 2000. Comparing simulated and measured values using mean squared deviation and its component. *Agron. J*. 92(2): 345-352.

Lascano, R. J. 2006. A recursive method to calculate potential evapotranspiration. In *Proc. Conf. on Water and Semiarid Lands: Innovative Approaches and Informed Decision-Making*, 15-17. Lubbock, Tex.: International Center for Arid and Semiarid Land Studies (ICASALS).

Lascano, R. J., and C. H. M. van Bavel. 2007. Explicit and recursive calculation of potential and actual evapotranspiration. *Agron. J.* 99(2): 585-590.

Lecina, S., A. Martínez-Cob, P. J. Pérez, F. J. Villalobos, and J. J. Baselga. 2003. Fixed canopy variable bulk canopy resistance for reference evapotranspiration estimation using the Penman-Monteith equation under semiarid conditions. *Agric. Water Mgmt.* 60(): 181-198.

McGinn, S. M., and K. M. King. 1990. Simultaneous measurements of heat, water vapour and CO_2 fluxes above alfalfa and maize. *Agric. Forest Meteorol.* 49(4): 331-349.

Marek, T. H., A. D. Schneider, T. A. Howell, and L. L. Ebeling. 1988. Design and construction of large weighing monolithic lysimeters. *Trans. ASAE.* 31(2): 477-484.

Maruyama, A., and T. Kuwagata. 2008. Diurnal and seasonal variation in bulk stomatal conductance of the rice canopy and its dependence on developmental stage. *Agric. Forest Meteorol.* 148(6-7): 1161-1173.

Milly, P. C. D. 1991. A refinement on the combination equations for evaporation. *Surveys in Geophysics* 12: 145-154.

Mölder, M., and A. Lindroth. 2001. Dependence of kB^{-1} factor on roughness Reynolds number for barley and pasture. *Agric. Forest Meteorol.* 106(2): 147-152.

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

Ottoni, T. B., A. D. Matthias, A. F. Guerra, and D. C. Slack. 1992. Comparison of three resistance methods for estimating heat flux under stable conditions. *Agric. Forest Meteorol.* 58(1-2): 1-18.

Paw, U. K. T., and W. Gao. 1988. Applications of solutions to non-linear energy budget equations. *Agric. Forest Meteorol.* 43(2): 121-146.

Penman, H. L. 1948. Natural evaporation from open water, bare soil, and grass. *Proc. Royal Soc. London A* 193(1032): 120-146.

Rose, C. W. 2006. *An Introduction to the Environmental Physics of Soil, Water, and Watersheds.* Cambridge, U.K.: Cambridge University Press.

Saugier, B., and N. Katerji. 1991. Some plant factors controlling evapotranspiration. *Agric. Forest Meteorol.* 54(2-4): 263-277.

Sellers, W. D. 1964. Potential evapotranspiration in arid regions. *J. Applied Meteorol*. 3(1): 98-104.

Sellers, W. D. 1965. *Physical Climatology.* Chicago, Ill.: The University of Chicago Press.

Sibbons, J. L. H. 1962. A contribution to the study of potential evapotranspiration. *Geografiska Annaler* 44(3-4): 279-292.

Thornthwaite, C. W. 1948. An approach toward a rational classification of climate. *Geograph. Rev.* 38(1): 55-94.

Tolk, J. A., S. R. Evett, and T. A. Howell. 2006. Advection influences on evapotranspiration of alfalfa in a semiarid climate. *Agron. J*. 98(6): 1646-1654.

Turner, N. C. 1970. Response of adaxial and abaxial stomata to light. *New Phytol.* 69(3): 647-653.

Van Bavel, C. H. M. 1967. Changes in canopy resistance to water loss from alfalfa induced by soil water depletion. *Agric. Meteorol*. 4(3): 165-170.

Van Bavel, C. H. M., and W. L. Ehrler. 1968. Water loss from a sorghum field and stomatal control. *Agron. J.* 60(1): 84-86.

Van Zyl, W. H., and J. M. De Jager. 1987. Accuracy of the Penman-Monteith equation adjusted for atmospheric stability. *Agric. Forest Meteorol.* 41(1-2): 57-64.