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ALFALFA REFERENCE ET MEASUREMENT and PREDICTION

S.R. Evett, T.A. Howell, R.W. Todd, A.D. Schneider, J.A. Tolk*

ABSTRACT

Alfalfa evapotranspiration (ET) is one of two common reference ET (ET_R) values. The other is grass ET. We tested Penman-Monteith (PM) and the 1982 Kimberly Penman (KP) equation predictions of ET_R against measured alfalfa ET under reference conditions. Alfalfa (*Medicago sativa*, var. Pioneer 5454) was grown in 1996 through 1999 on Pullman clay loam (Torrertic Paleustoll) at Bushland, TX. The crop was well-watered with a lateral move sprinkler. Monolithic weighing lysimeters (3-m by 3-m by 2.4-m deep) measured ET every half hour to 0.05 mm precision. Yields were 16.5, 16.4, 20.6, and 15.2 dry Mg ha^{-1} in 1996 through 1999. Crop water use averaged 1.01 m per year in 1996 and 1997, and was 1.16 m in 1998. Daily ET in this windy, semi-arid environment occasionally exceeded 14 mm. Daily alfalfa ET_R predicted using PM methods and half-hourly weather data compared well with our measurements (regression r^2 of 0.94, SE of 0.6 mm, slope of 0.94, and intercept of 0.2 mm). Use of daily weather data increased the SE to 0.8 mm (r^2 of 0.90, slope of 0.98) and introduced a positive offset of 0.7 mm. The KP equation used with daily weather data produced more biased predictions (r^2 of 0.91, SE of 0.7 mm, intercept of 0.9 mm, and slope of 0.88). The ASCE Manual 70 methods for predicting net radiation from solar irradiance worked well when applied to half-hourly data (r^2 of 0.97, SE of 0.6 MJ/m^2, and slope of 1.03). But these methods applied to daily data produced biased results (r^2 of 0.94, SE of 0.8 MJ/m^2, intercept of 1.5 MJ/m^2, and slope of 0.85). Use of the KP net radiation equations with daily data produced slightly less biased results (r^2 of 0.97, SE of 0.6 MJ/m^2, intercept of 0.7 MJ/m^2, and slope of 0.87). Alfalfa ET was 1.15 times grass ET.
Keywords. Evapotranspiration, Alfalfa, Water Use, Penman-Monteith, Kimberly-Penman, Grass

INTRODUCTION

Current widely used irrigation scheduling procedures, including the North Plains PET network (Marek et al., 1996), rely on the $K_C ET_R$ paradigm for prediction of daily crop water use (ET). This concept relies on a daily reference ET measurement or prediction (ET_R) multiplied by a crop coefficient (K_C) to predict water use. The crop coefficient is determined from prior measurements of K_C=ET/ET_R vs. growing degree days or growth stage. Different reference ET crops have been considered such as well-watered and fertilized alfalfa and grass (Jensen et al., 1970; Wright, 1982; Doorenbos and Pruitt, 1977; Allen et al., 1989). But, problems with maintenance, cutting, lysimeter design and operation, and associated weather measurements have combined to make these measurements often inaccurate (Allen et al., 1994a).

Great effort has gone into refining and testing equations for weather based ET_R calculations; and Allen et al. (1994a) recommended that, in studies aimed at determining crop coefficients, ET_R routinely be calculated using the Penman-Monteith formula rather than measured. However, crop coefficients are still found by measuring ET directly and dividing ET by ET_R. Therefore all of the problems associated with field measurements of ET_R are not dismissed by using a weather based calculation method since these problems are equally as important for field measurements of crop ET as for determination of K_C. There is increasing evidence that theoretical reference ET formulations do not accurately predict actual reference crop ET in many environments, especially semi-arid and arid ones (Steduto et al., 1996). There is also much evidence that crop coefficients are not transferrable from one region to another, regardless of the reference ET method.

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*S.R. Evett, Soil Scientist; T.A. Howell, Research Leader and Agricultural Engineer; R.W. Todd, Plant Physiologist, A.D. Schneider, Agricultural Engineer, and J.A. Tolk, Plant Physiologist, Water Management Research Unit, USDA-ARS, Bushland, TX. E-mail: srevett@ag.gov (Internet: http://www.cprl.ars.usda.gov/).

Allen et al. (1994a) provided evidence for this lack of transportability by comparing the estimated ratio of alfalfa to grass ET_R 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. It is important to note that this variance of ratios applies equally as well to the ratio of a particular crop ET to grass ET_R (i.e. the crop coefficient, ET/ET_R) thus calling into question the transportability of crop coefficients. Using an energy balance model, Annandale and Stockle (1994) studied variability of full canopy cover K_C, as influenced by changes in solar radiation, air temperature, VPD, and wind speed, for a variety of different plant heights and canopy resistances. Variability in K_C increased as crop height increased and as canopy resistance decreased. Variability in K_C decreased if an alfalfa reference ET was used rather than grass ET_R and they recommended: 1) using alfalfa ET_R, and 2) development of methods for directly estimating crop ET.

Jensen et al. (1990) evaluated 19 methods of estimating daily ET_R and ranked the PM method the highest, but adjustments to roughness length, leaf area index, and bulk surface resistance were applied to the PM through measurements of mean crop height while the other methods were not adjusted in this way. This inclusion of LAI effects on canopy resistance and plant height effects on the surface roughness parameter significantly improved the performance of the PM method (Jensen et al., 1990). Wright (1982) modified the Penman combination equation by adjusting the wind function and surface albedo for time of year to more accurately predict alfalfa ET at Kimberly, Idaho. This "1982 Kimberly Penman" method ranked second best in the evaluation done by Jensen et al. (1990). Our objective was to evaluate Penman-Monteith and 1982 Kimberly Penman equations for alfalfa reference ET by comparison with ET from well-watered, full-cover alfalfa in our highly advective semi-arid environment.

MATERIALS and METHODS

Alfalfa variety Pioneer 5454[**] was seeded at a rate of 28 kg ha^{-1} on September 13 and 14, 1995, with a grain drill on 20 cm spacing using two passes of the drill. The two fields were irrigated with a Lindsay lateral move sprinkler as needed to maintain a well-watered condition. The fields are contiguous, being separated only by a sprinkler wheel track; and each field is a 5 ha square with a weighing lysimeter in its center. The fields are designated NorthEast (NE) and SouthEast (SE), as are the lysimeters.

Evapotranspiration and Micrometeorological Measurements

Lysimeter mass was measured with 0.05 mm precision and reported on a half-hour basis (Dusek et al., 1987). Micrometeorological measurements were made at 6 s intervals and reported as 30 min averages. Due to better fetch, measurements at the NE lysimeter will be described here but all measurements were made on the SE lysimeter as well. Lysimeter inside surface area was 9 m^2 but the crop canopy extended from both inside and outside the lysimeter to cover the 0.04 m wide lysimeter walls. We considered that the actual canopy surface area contributing to ET from the lysimeter was thus extended to an area 3.02 by 3.02-m square. Thus, we applied a correction factor to lysimeter ET of $9(3.02)^{-2} = 0.9868$. Over the lysimeters, net radiation was measured with REBS net radiometers (Q*5.5, Seattle, WA). Net radiometers were checked against the sum of net radiation components as measured by an albedometer (model CM14, Kipp & Zonen, Delft, Holland) and two pyregeometers (Kipp & Zonen model CG2, and Eppley Laboratories, Inc model PIR, Newport, RI). Soil heat flux was measured with four heat flux plates (REBS HFT-1) buried at 5 cm depth with averaging thermocouples (parallel connected) buried at 2 and 4 cm above each plate. Rainfall was measured by a tipping bucket raingage (Qualimetrics 611-B) mounted to place its orifice at 1 m above ground level at each lysimeter. Grass reference ET and net radiation, and wind speed, air and dew point temperatures, and solar irradiance were measured at the nearby grass weather station as described in Howell et al. (1998). Specifically, air and dew point temperatures were measured at 1.5-m height, and wind speed was measured at 2-m height, except in 1999 when dew point

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[**]The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

and wind speed measurements from the Bushland USDA-ARS meteorological station were used (2-m height).

Leaf Area Index (LAI), Staging, and Harvest

Leaf area was measured periodically between and at each harvest. In each field, four 1 m square areas were harvested and quickly bagged in plastic bags and placed in a cooler. These were weighed for fresh weight. Subsamples were taken from each bag (about 8% of sample wet mass), weighed for fresh weight and the leaves pulled off and leaf area measured with a leaf area meter (Licor LI-3100, Lincoln, NE). The leaf area meter was checked periodically with a 50 cm^2 standard disk. Leaves and stems of the subsamples were saved, dried and weighed to find the ratio of dry leaf mass to stem mass. The ratio of leaf area to fresh weight from the subsamples was used to calculate leaf area for the 1 m square samples from total fresh weight.

Harvest times balanced the need for data collection, crop quality, field operations, and field condition (wetness). These constraints allowing, harvest was done in the period from 10% to 50% bloom. Alfalfa was swathed with conditioning, cured, and baled into small, square bales. At harvest, the alfalfa from the lysimeters was hand harvested, sub-sampled for LAI, and placed quickly in plastic bags and fresh weight determined. Growth stage and plant height were measured at every LAI measurement date.

ET Prediction

The Penman-Monteith equation is

$$\lambda ET = \frac{\Delta(R_n - G) + \rho c_P(e_a - e_d)/r_a}{\Delta + \gamma(1 + r_s/r_a)} \tag{1}$$

where λET is latent heat flux , R_n is net radiation, and G is soil heat flux (all in MJ m^{-2} s^{-1}); Δ is the slope of the saturation vapor pressure-temperature curve (kPa $°C^{-1}$), ρ is air density (kg m^{-3}), c_P is the specific heat of air (kJ kg^{-1} $°C^{-1}$), e_a is saturated vapor pressure of the air at ambient temperature and e_d is the saturated vapor pressure at the dew point temperature (kPa), (e_a - e_d) is the vapor pressure deficit (VPD), r_a is the aerodynamic resistance (s m^{-1}), r_s is the canopy resistance (s m^{-1}), and γ is the psychrometric constant (kPa $°C^{-1}$).

Penman-Monteith ET was calculated using methods from ASCE Handbook 70 (Jensen et al., 1990). Canopy resistance was calculated as

$$r_S = r_l(0.5LAI)^{-1} \tag{2}$$

where r_l is the stomatal resistance taken as 100 s/m, and where LAI was calculated as

$$LAI = 5.5 + 1.5\ln(h_C) \tag{3}$$

where h_c is crop height (taken as 0.5 m). Aerodynamic resistance, r_a, (s m^{-1}) was calculated using Eq. 6.18 in ASCE Handbook 70 for which the zero plane displacement height, d, is calculated as

$$d = 2/3\ h_C \tag{4}$$

the roughness length for momentum, z_{om}, is calculated as

$$z_{om} = 0.123\ h_C \tag{5}$$

and the roughness length for heat and water vapor transport is

$$z_{oh} = 0.1\ z_{om} \tag{6}$$

For the PM equation, net radiation was calculated from Eqs. 3.5, and 3.15-3.17 in ASCE Handbook 70 with albedo, α, taken as 0.23, and a = 1.35, b = -0.35, a_1 = 0.35, and b_1 = -0.145. For half-hourly calculations at night the ratio of solar irradiance, Rs, to clear sky irradiance, Rso, was taken as 0.7 (Allen et al., 1994b).

For the 1982 Kimberly Penman method, the time of year was assumed to influence albedo according to Eq. 6.67 in ASCE Handbook 70; parameter a_1 varied with time of year according to Eq. 6.68; b_1 was taken as -0.139. Parameters a and b were taken as a = 1.126 when Rs/Rso > 0.7, and a = 1.017 otherwise; and b = -0.07 when Rs/Rso > 0.7, and b = -0.06 otherwise. Then net radiation was calculated using Eqs. 3.5, and 3.15-3.17 in ASCE Handbook 70.

For half-hourly calculations, soil heat flux was calculated as 0.1 R_n for daytime values and 0.5R_n for nighttime values (Allen et al., 1994b). For daily calculations, soil heat flux, G (MJ/m^2), was calculated as

$$G = Cs\ ds(T_i - T_{m3}) \tag{7}$$

where Cs was soil specific heat taken as 2.1 MJ m^{-3} $°C^{-1}$, ds was the soil depth for computing soil heat flux taken as 0.18 m, T_i was the current day's mean air temperature approximated as the mean of the minimum and maximum air temperatures, and T_{m3} was the mean air temperature over the previous three days.

The Penman combination equation for daily values in MJ m^{-2} is given by Eq. 6.15c in ASCE Handbook 70. In this equation, the wind function, W_f, is

$$W_f = a_w + b_w U_2 \tag{8}$$

Our 1982 Kimberly Penman ET values were calculated using the wind function where a_w and b_w are functions of the day of the year as described by Eqs. 6.27 and 6.28a in ASCE Handbook 70.

RESULTS

Yield from four cuttings was 16.5, 16.4, and 15.2 dry Mg ha^{-1} in 1996, 1997, and 1999, respectively. In 1998, yield from five cuttings was 20.6 dry Mg ha^{-1}. Irrigation averaged 1007 mm per year. Leaf area index (LAI) exceeded 6 for the first cutting with lower LAI values for subsequent cuttings. Plant height exceeded 0.6 m for the first two cuttings of 1996. The relationship between LAI and plant height was not constant (Evett et al., 1998) and did not match the function suggested by Allen et al. (1994b). Lodging that occurred before the first and second cuttings in 1996 caused the plant height to decline in some areas of the field and lysimeters. Lodging of the very heavy crop before the first two cuttings was worsened by overhead spray irrigations and rain. The heavy crop was probably due to residual nitrogen in the field from previous corn and wheat crops. Soil nitrogen samples taken to 4.3-m depth showed uptake of residual nitrogen by the alfalfa in the first two crop years (data not shown). Lodging was less of a problem in later years.

Measured ET followed different patterns each year (Fig. 1, omitted irrigation and rain days). Early 1996 was marked by high evaporative demand, with average ET of 8.5 mm d^{-1} until about August 15, after which mean ET was only 4.8 mm d^{-1}. In 1997, there was a period of higher ET (10 mm d^{-1}) in mid-season; and a similar period of 9.5 mm d^{-1} ET was observed in 1998. In 1999, the low ET reflected the cool and wet weather for most of the season. Mean ET values were 7.1, 6.7, 7.3, and 6.1 mm d^{-1} in 1996 through 1999, respectively. In 1996 and 1997, peak ET reached nearly 16 mm d^{-1}, and in 1998 it reached 18 mm d^{-1}, while in 1999 it reached only 13 mm d^{-1}. These data confirm that evaporative demand in this region of the Southern High Plains is among the highest reported anywhere.

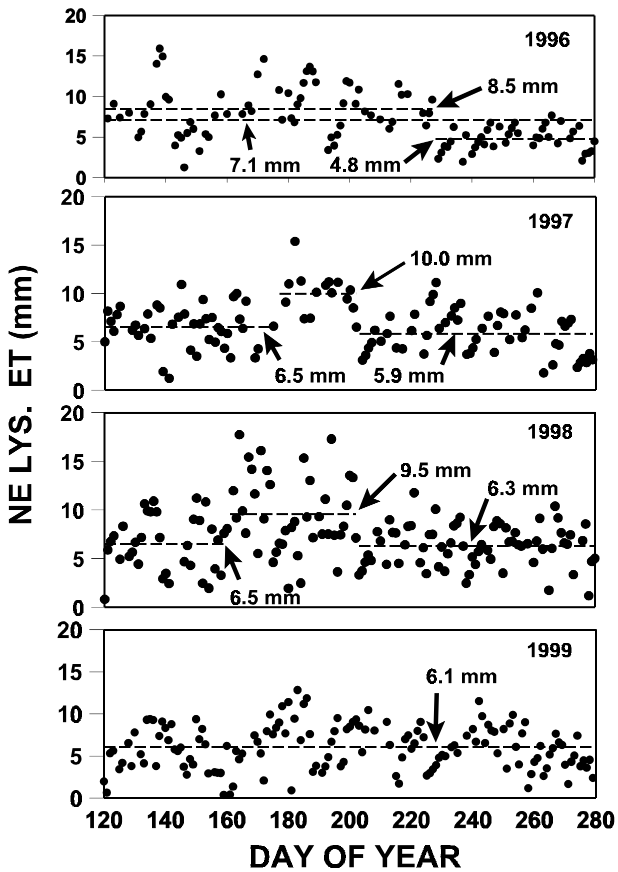

Fig. 1. NE lysimeter evapotranspiration for four seasons of alfalfa. Dashed lines indicate mean ET over the intervals they cross.

We compared estimated ET with measured ET for days when leaf area index was greater than 3; while omitting days when the crop was not well-watered (drying period before harvest), when the crop was lodged, and when irrigation or rainfall compromised the integrity of the water balance calculations for measured ET (Table 1). Using half-hourly data with the PM equation resulted in excellent predictions of non-stressed full-cover alfalfa ET for 1996 and 97, but tended to under-predict ET at the high end in 1998 and 99 (slope less than unity and a positive intercept. Overall, the half-hourly PM method produced the smallest standard error and largest r^2 value. Calculations using daily data resulted in predictions that were almost as good, but exhibited a positive offset approaching 0.7 mm in 1997, increasing to just over 1 mm in 1998-99. The standard error of estimate for the combined data from all years was 0.83 mm for the daily PM, which is close to the 0.77 mm reported by Jensen et al. (1990). The 1982 Kimberly Penman equation produced biased estimates in all years, tending to over-predict ET at low ET rates and under-predict at high ET rates. This was tied to predictions of net radiation that were biased under our conditions (Table 1). The 0.69-mm SE value for all data was less than the 0.88 mm reported by Jensen et al. (1990) for this method.

Net radiation was very well predicted when half-hourly data were used and suggestions for night time Rn calculation from Allen et al. (1994b) were used with the methods suggested in ASCE Handbook 70 (Table 1). Using daily data resulted in biased predictions of Rn using Handbook 70 methods, with over-estimation at low Rn values and underestimation at high values. Using the time of year dependent net radiation calculation methods of Wright (1982) (Kimberly Penman 1982) reduced but did not eliminate the bias. In both 1997 and 1998, there was little difference between the Q*5.5 measured Rn and the sum of measured components, regardless of which pyrgeometer was used. For soil heat flux, using the method of Allen et al. (1994b), which estimates heat flux as 0.1 of Rn during daytime and 0.5 of Rn during nighttime, resulted in smaller errors than did the ASCE Handbook 70 methods. While neither method was very accurate, neither error was large (Evett et al., 1998).

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Table 1. Daily evapotranspiration, ET (mm), and net radiation, Rn (MJ m^{-2}), estimated by three methods[a] compared with lysimeter measured values, ET_L, and Rn_L, for 1996 through 1999.

1996	Regression Equation	r^2	SE	N
	$ET_{0.5PM} = -0.15 + 0.97(ET_L)$	0.97	0.43 mm	59
	$ET_{PM} = 0.34 + 1.01(ET_L)$	0.95	0.58 mm	59
	$ET_{K82} = 0.70 + 0.91(ET_L)$	0.97	0.44 mm	59
1997				
	$ET_{0.5PM} = -0.14 + 0.96(ET_L)$	0.93	0.65 mm	86
	$ET_{PM} = 0.69 + 0.97(ET_L)$	0.86	0.95 mm	86
	$ET_{K82} = 0.89 + 0.87(ET_L)$	0.88	0.81 mm	86
1998				
	$ET_{0.5PM} = 1.00 + 0.89(ET_L)$	0.95	0.52 mm	54
	$ET_{PM} = 1.02 + 0.97(ET_L)$	0.90	0.79 mm	54
	$ET_{K82} = 0.89 + 0.87(ET_L)$	0.90	0.70 mm	54
1999				
	$ET_{0.5PM} = 0.51 + 0.87(ET_L)$	0.93	0.62 mm	28
	$ET_{PM} = 1.07 + 0.91(ET_L)$	0.87	0.91 mm	28
	$ET_{K82} = 1.31 + 0.88(ET_L)$	0.94	0.59 mm	28
1996 through 1999 combined				
	$ET_{0.5PM} = 0.16 + 0.94(ET_L)$	0.94	0.62 mm	227
	$ET_{PM} = 0.69 + 0.98(ET_L)$	0.90	0.83 mm	227
	$ET_{K82} = 0.87 + 0.88(ET_L)$	0.91	0.69 mm	227
Net Radiation 1996 through 1999 combined				
	$Rn_{0.5PM} = 0.08 + 1.03(Rn_L)$	0.97	0.65 MJ m^{-2}	345
	$Rn_{PM} = 1.52 + 0.85(Rn_L)$	0.94	0.77 MJ m^{-2}	345
	$Rn_{K82} = 0.68 + 0.87(Rn_L)$	0.97	0.56 MJ m^{-2}	345

[a] Methods are indicated by subscripts as follows
0.5 PM = Penman Monteith with half-hourly calculations
PM = Penman Monteith with daily calculations
K82 = Kimberly Penman 1982 with daily calculations

Comparison of lysimeter measured alfalfa and grass ET was limited to 22 data points in 1996 when conditions were ideal. The ratio of alfalfa to grass ET was 1.15, which is somewhat lower than would be predicted on the basis of PM estimates of grass and alfalfa ET. For instance, Allen et al. (1994a) calculated ratios averaging 1.35 for six arid sites, and averaging 1.28 for five humid sites. The PM equation tends to under-estimate grass ET for our location (Howell et al., 1998); and the ratio of alfalfa to grass PM ET would be expected to be higher than 1.15.

CONCLUSIONS

The Penman-Monteith equation, with methods for estimating aerodynamic and canopy resistances and net radiation from ASCE Handbook 70, predicted alfalfa ET well under reference ET conditions at our location (plant height assumed equal to 0.5 m and LAI equal to 4.5). Consideration of the results of this paper and those of Howell et al. (1998) leads to the conclusions that alfalfa is a better reference crop than is grass, and that the PM equation for alfalfa worked better than the PM equation for grass in our environment.

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