**Paper No. 982123**
**An ASAE Meeting Presentation**

# EVAPOTRANSPIRATION OF IRRIGATED ALFALFA IN A SEMI-ARID ENVIRONMENT

**by**

| S.R. Evett | T.A. Howell | R.W. Todd | A.D. Schneider | J.A. Tolk |
|---|---|---|---|---|
| Soil Scientist | Research Leader | Plant Physiologist | Agricultural Engineer | Plant Physiologist |

**USDA-Agricultural Research Service**
**Conservation and Production Research Laboratory**
**2300 Experiment Station Road**
**Bushland, TX 79012, USA**
**http://www.cprl.ars.usda.gov**

**Written for presentation at the**
**1998 ASAE Annual International Meeting**
**sponsored by ASAE**

**Disney's Coronado Springs Resort**
**Orlando, Florida**
**July 12-16, 1998**

**Summary:** We tested Penman-Monteith (PM) and Kimberly Penman (1982) equation predictions of reference evapotranspiration ($ET_R$) against alfalfa (*Medicago sativa*, var. Pioneer 5454) ET measured to 0.05 mm precision with weighing lysimeters under reference conditions in 1996-97 on Pullman clay loam (Torrertic Paleustoll) at Bushland, TX. Yield from 4 cuttings was 16.5 dry t/ha in 1996, and 16.4 t/ha in 1997. Crop water use averaged 1.01 m per year. Daily alfalfa $ET_R$ predicted using PM methods and half-hourly weather data compared well with our measurements (regression $r^2$ of 0.95, SE of 0.6 mm, and slope of 0.97). Use of daily weather data increased SE to 0.8 mm ($r^2$ of 0.90, slope of 0.99) and introduced a positive offset of 0.5 mm. The Kimberly Penman (1982) equation used with daily weather data produced biased predictions ($r^2$ of 0.91, SE of 0.7 mm, intercept of 0.8 mm, and slope of 0.88).

**Keywords:** alfalfa, Penman Monteith, reference evapotranspiration, yield, water use, net radiation

# EVAPOTRANSPIRATION OF IRRIGATED ALFALFA IN A SEMI-ARID ENVIRONMENT[1]


| S.R. Evett | T.A. Howell | R.W. Todd | A.D. Schneider | J.A. Tolk[2] |
|---|---|---|---|---|
| Member | ASAE Fellow | | Member Engineer | |



## ABSTRACT

Evapotranspiration (ET) from well-watered alfalfa with no limitations to growth is one of two common reference ET ($ET_R$) values used to scale ET from other crops to obtain crop coefficient values for irrigation scheduling - the other is grass reference ET. We tested Penman-Monteith (PM) and Kimberly Penman (1982) equation predictions of $ET_R$ against measured alfalfa ET under reference conditions. Alfalfa (*Medicago sativa*, var. Pioneer 5454) was seeded at 28 kg/ha in Sept. 1995 and grown in 1996 and 1997 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 in surface area, and 2.4-m deep) measured ET every half hour to 0.05 mm precision. Yield from 4 cuttings was 16.5 dry t/ha in 1996, and 16.4 t/ha in 1997. Crop water use averaged 1.01 m per year. 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 0.95, SE of 0.6 mm, and slope of 0.97). Use of daily weather data increased the SE to 0.8 mm ($r^2$ of 0.90, slope of 0.99) and introduced a positive offset of 0.5 mm. The Kimberly Penman (1982) equation used with daily weather data produced biased predictions ($r^2$ of 0.91, SE of 0.7 mm, intercept of 0.8 mm, and slope of 0.88). The ASCE Handbook 70 methods for predicting net radiation from solar irradiance worked well when applied to half-hourly data ($r^2$ of 0.98, 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 0.95, SE of 0.7 MJ $m^{-2}$, intercept of 1.5 MJ $m^{-2}$, and slope of 0.84). Use of the 1982 Kimberly net radiation equations with daily data produced slightly less biased results ($r^2$ of 0.97, SE of 0.5 MJ $m^{-2}$, intercept of 0.6 MJ $m^{-2}$, and slope of 0.86). Alfalfa ET was 1.15 times grass ET from a nearby separate experiment in 1996.



**Keywords:** alfalfa, Penman Monteith, Kimberly Penman, reference evapotranspiration, yield, water use, net radiation


---

[1]Contribution of the U.S. Department of Agriculture, Agricultural Research Service, Southern Plains Area, Conservation and Production Research Laboratory, Bushland, Texas. This work was prepared by a USDA employee as part of his official duties and cannot legally be copyrighted. The fact that the private publication in which the article appears is itself copyrighted does not affect the material of the U.S. Government, which can be reproduced by the public at will.


[2]Soil Scientist, Research Leader/Agricultural Engineer, Plant Physiologist, Agricultural Engineer, and Plant Physiologist, respectively, Conservation and Production Research Laboratory, P.O. Drawer 10, Bushland, TX 79012. First author e-mail: srevett@ag.gov, Internet: http://www.cprl.ars.usda.gov

## 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 ($ET_R$) measurement or prediction 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 increasingly more 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.

Allen et al. (1994a) provided evidence for this lack of transportability by comparing the 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 $ET_R$ 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 (Allen et al., 1994a). 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). 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[3] 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 (Fig. 1). 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

**Figure 1**. Instrumentation over the SE lysimeter, June 18, 1996. Sprinkler irrigation is occurring.

Lysimeter mass was measured on a 6 s interval with 15 min averages reported (later consolidated to 30 min averages) using the methods reported in Dusek et al. (1987), which result in a precision of 0.05 mm. Evapotranspiration was calculated from the water balance (including rainfall and irrigation occurring in each 30 min period). 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 $9(3.02)^{-2} = 0.9868$. Grass reference ET and net radiation, and additional micrometeorological variables, 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.

Over the lysimeters, wind speed (Met One 014A, Grants Pass, OR), and relative humidity and air temperature (Rotronics MP100, Huntington, NY) were measured at 2 m above ground surface (Fig. 1). Transmitted PAR was measured at ground level (Licor LI-191SB, Lincoln, NE). Several radiation sensors were mounted on a bar at 1 m above the soil surface: Surface temperature (canopy and/or soil) was measured by infrared thermometer (Exergen IRT/C.2-T-80) pointed at 60° below horizontal). Net radiation was measured with REBS net radiometers (Q*5.5, Seattle, WA). Reflected short wave radiation was measured by solar radiometer (Eppley 8-48, Newport, RI). The Eppley 8-48 was replaced in summer 1996 by the Kipp and Zonen CM14 albedometer (Delft, Holland), which measured incoming and reflected short wave radiation. Reflected PAR was measured by the Licor LI-190SB sensor.

---

[3]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.

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.

Leaf Area Index (LAI) and Staging

Leaf area was measured every two weeks 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.

At harvest the alfalfa from the lysimeters was harvested and placed quickly in plastic bags and fresh weight determined. Three subsamples from each lysimeter were weighed for fresh weight and leaf area determined. At harvest the leaf area in the field was also determined as stated in the previous paragraph. Growth stage and plant height were measured at every LAI measurement date.

Harvest

Harvest was at times that 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. Lysimeters were hand-harvested for total fresh weight and biomass (Fig. 2).

**Figure 2**. Hand harvest of lysimeter.

ET Prediction

The Penman-Monteith equation is

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

where $\lambda$ET is latent heat flux , $R_n$ is net radiation, and G is soil heat flux (all in MJ $m^{-2}$ $s^{-1}$); $\Delta$ is the slope of the saturation vapor pressure-temperature curve (kPa $°C^{-1}$), $\rho$ 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 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 $\gamma$ is the psychrometric constant (kPa $°C^{-1}$).

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

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

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

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

where $h_c$ is crop height (taken as 0.5 m). Aerodynamic resistance, $r_a$, (s $m^{-1}$) was calculated as

$$r_a = \frac{\ln\left(\frac{z_m - d}{z_{om}}\right)\ln\left(\frac{z_h - d}{z_{oh}}\right)}{k^2 U_z} \tag{4}$$

where $z_m$ (m) is the measurement height (2 m) for wind speed, $U_z$, (m/s), $z_h$ (m) is measurement height (1.5 m) for air temperature and relative humidity, k is 0.41, and the zero plane displacement height, d, is calculated as

$$\mathbf{d = 2/3\ h_C} \tag{5}$$

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

$$\mathbf{z_{om} = 0.123\ h_C} \tag{6}$$

and the roughness length for heat and water vapor transport is

$$\mathbf{z_{oh} = 0.1\ z_{om}} \tag{7}$$

For the PM equation, net radiation was calculated from Eqs. 3.5, and 3.15-3.17 in ASCE Handbook 70 with albedo, $\alpha$, 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; and parameters a and b were taken as

$$\mathbf{a = 1.126, \qquad Rs/Rso > 0.7} \tag{8a}$$

$$\mathbf{b = -0.07, \qquad Rs/Rso > 0.7} \tag{8b}$$

$$\mathbf{a = 1.017, \quad Rs/Rso <= 0.7} \tag{8c}$$

$$\mathbf{b = -0.06, \quad Rs/Rso <= 0.7} \tag{8d}$$

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

$$\mathbf{G = Cs\ ds(T_i - T_{m3})} \tag{9}$$

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

$$\lambda ET = \frac{\Delta(R_n - G)}{\Delta + \gamma} + \frac{\gamma}{\Delta + \gamma}\, 6.43 W_f (e_a - e_d) \tag{10}$$

where $W_f$ is the wind function (Eq. 6.15c, ASCE Handbook 70). Our 1982 Kimberly Penman ET values were calculated using the wind function

$$\mathbf{W_f = a_w + b_w U_2} \tag{11}$$

where $a_w$ and $b_w$ are described by Eqs. 6.27 and 6.28a in ASCE Handbook 70

$$\mathbf{a_w = 0.4 + 1.4exp\{-[(DOY - 173)/58]^2\}} \tag{12}$$

$$\mathbf{b_w = 0.605 + 0.345exp\{-[(DOY - 243)/80]^2\}} \tag{13}$$

where DOY is the day of year and Eq. 12 is for $U_2$ in m $s^{-1}$.

## RESULTS

Yield from four cuttings was 16.5 dry t/ha in 1996, and 16.4 dry t/ha in 1997. Irrigation averaged 1007 mm per year. Leaf area index (LAI) exceeded 6 for the first cutting with lower LAI values for subsequent cuttings (Fig. 3). Plant height exceeded 0.6 m for the first two cuttings of 1996. The relationship between LAI and plant height was not constant; and did not match the function suggested by Allen et al. (1994b) (Fig. 4). Lodging that occurred before the first and second cuttings in 1996 caused the plant height to decline (Fig. 4) 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).

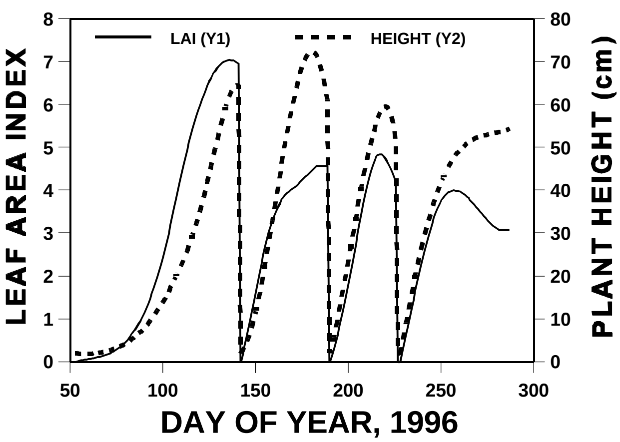


**Figure 3** Fitted curves of leaf area index (LAI) and plant height.

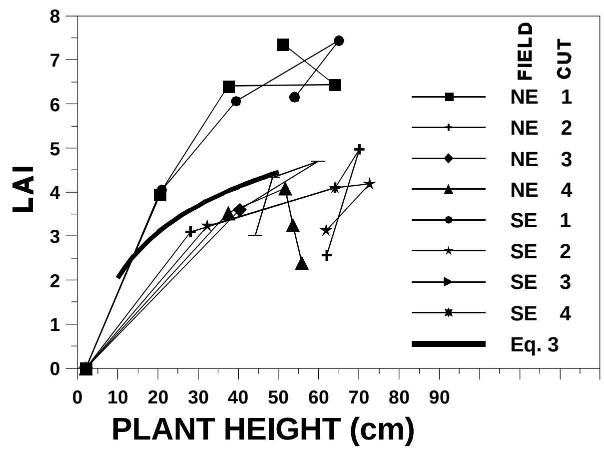


**Figure 4**. Plot of measured leaf area index (LAI) vs. plant height illustrating discrepancy with Eq. 3.

Measured evapotranspiration in 1996 and 1997 followed different patterns (Fig. 5, 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, while ET did decrease near the end of the season, there was not markedly higher ET early in the season. Mean ET for 1997 was 6.7 mm d$^{-1}$ compared with a seasonal mean of 7.1 mm d$^{-1}$ for 1996. In both years peak ET reached nearly 16 mm d$^{-1}$. Data for 1998 not included in this report show a peak ET of 18 mm d$^{-1}$ (measured on both lysimeters). These data confirm that evaporative demand in this region of the Southern High Plains is amongst the highest reported anywhere.

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, Fig. 6). Using half-hourly data with the PM equation resulted in excellent predictions of non-

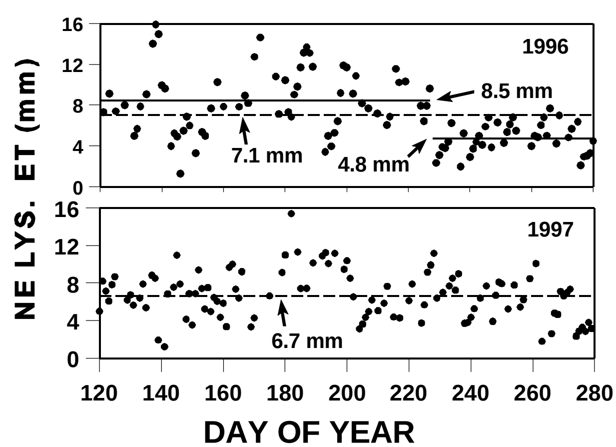


**Figure 5**. Alfalfa ET in 1996 and 1997 from the NE lysimeter at Bushland. Dashed lines indicate growing season means. Solid lines in the 1996 plot indicate means before and after August 15.

stressed full-cover alfalfa ET for both years. Calculations using daily means and maximum and minimum temperatures resulted in predictions that were almost as good, but exhibited a slight positive offset approaching 0.7 mm in 1997. The 1982 Kimberly Penman equation tended to over predict ET at low ET rates and under predict at high ET rates. As will be discussed below, this was tied to predictions of net radiation that were biased under our conditions.

**Table 1.** Evapotranspiration, ET (mm), estimated by three methods[1] compared with lysimeter measured ET, $ET_L$, for 1996 and 1997.

| 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 |
| 1996 and 1997 combined | | | | |
| | $ET_{0.5PM} = -0.12 + 0.97(ET_L)$ | 0.95 | 0.57 mm | 145 |
| | $ET_{PM} = 0.54 + 0.99(ET_L)$ | 0.90 | 0.82 mm | 145 |
| | $ET_{K82} = 0.83 + 0.88(ET_L)$ | 0.91 | 0.69 mm | 145 |

[1] 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

In contrast to using Eqs. 2 and 3 with a standard plant height of 0.5 m, we then used the PM equation on 1996 data with plant height and LAI from the fitted curves (results not shown). Estimates of ET were less precise with SE of 1.4 mm and were more biased with greater over prediction at the larger ET values. This may illustrate some fragility in Eqs. 3-7 for conditions that are not close to the standard conditions of $h_C = 0.5$ m and LAI = 4.5. On the other hand, the fitted curves of crop height only approximate the actual plant height on any given day; due to partial and temporary lodging that tended to occur after heavy irrigations or rain.

Comparison of lysimeter measured alfalfa and grass ET was limited to 22 data points in 1996 when conditions were ideal (Fig. 7). 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.

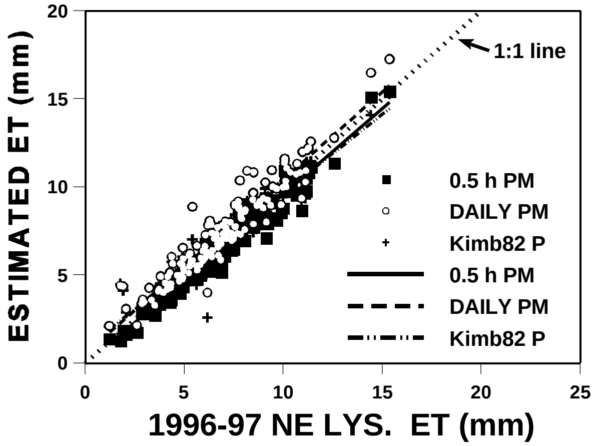


**Figure 6**. Penman-Monteith ET vs. measured ET for leaf area index (LAI) >= 3. Equations 2 and 3 were used with crop height set to 0.5 m.

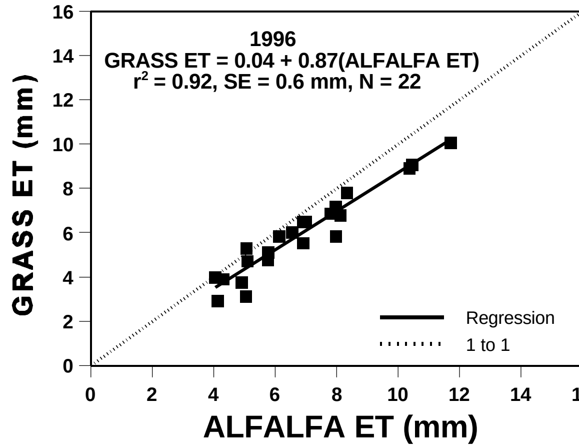


**Figure 7**. Comparison of grass ET with alfalfa ET, measured values for 1996.

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.

Net radiation was very well predicted when half-hourly data were used and suggestions for night time Rn calculation from Allen et al. (1994) supplemented the methods suggested in ASCE Handbook 70 (Table 2, Fig. 8). 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. We checked our net radiometers against the sum of net radiation components as measured by an albedometer (model CM14, Kipp & Zonen, Delft, Holland) and two pyrgeometers (Kipp & Zonen model CG2, and Eppley Laboratories, Inc model PIR, Newport, RI). 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, leading us to believe that our measured net radiation values are likely correct.

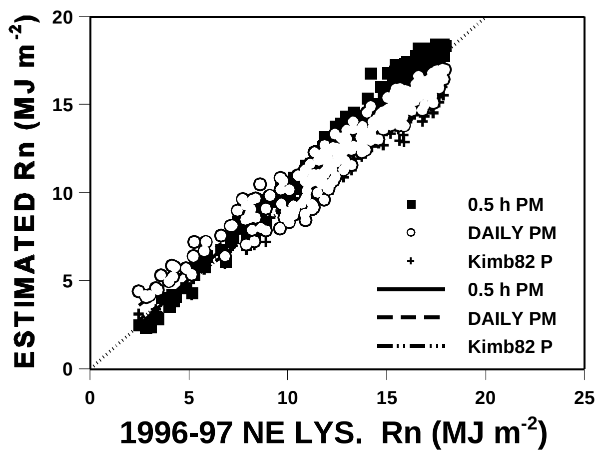


**Figure 8**. Comparison of net radiation ($R_n$) computed with ASCE Handbook 70 methods with $R_n$ measured using a REBS Q*5.5 net radiometer.

**Table 2.** Net radiation, Rn (MJ $m^{-2}$), estimated by three methods[1] compared with lysimeter measured Rn, $Rn_L$, for 1996 and 1997.

| 1996 | Regression Equation | $r^2$ | SE | N |
|---|---|---|---|---|
| | $Rn_{0.5PM} = -0.13 + 1.03(Rn_L)$ | 0.98 | 0.55 MJ $m^{-2}$ | 105 |
| | $Rn_{PM} = 1.32 + 0.85(Rn_L)$ | 0.95 | 0.73 MJ $m^{-2}$ | 105 |
| | $Rn_{K82} = 0.53 + 0.87(Rn_L)$ | 0.97 | 0.52 MJ $m^{-2}$ | 105 |
| 1997 | | | | |
| | $Rn_{0.5PM} = -0.02 + 1.04(Rn_L)$ | 0.98 | 0.55 MJ $m^{-2}$ | 158 |
| | $Rn_{PM} = 1.70 + 0.84(Rn_L)$ | 0.95 | 0.73 MJ $m^{-2}$ | 158 |
| | $Rn_{K82} = 0.72 + 0.86(Rn_L)$ | 0.98 | 0.49 MJ $m^{-2}$ | 158 |
| 1996 and 1997 combined | | | | |
| | $Rn_{0.5PM} = -0.08 + 1.03(Rn_L)$ | 0.98 | 0.56 MJ $m^{-2}$ | 263 |
| | $Rn_{PM} = 1.53 + 0.84(Rn_L)$ | 0.95 | 0.74 MJ $m^{-2}$ | 263 |
| | $Rn_{K82} = 0.63 + 0.86(Rn_L)$ | 0.97 | 0.51 MJ $m^{-2}$ | 263 |

[1] 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

**Table 3.** Soil heat flux, G (MJ $m^{-2}$), estimated by two methods[1] compared with lysimeter measured G, $G_L$, for 1996 and 1997. Ten days post-harvest data omitted.

| 1996 | Regression Equation | $r^2$ | SE | N |
|---|---|---|---|---|
| | $G_{0.5PM} = 0.66 + 0.40(G_L)$ | 0.33 | 0.29 MJ $m^{-2}$ | 143 |
| | $G_{PM} = 0.07 + 1.52(G_L)$ | 0.42 | 0.93 MJ $m^{-2}$ | 143 |
| 1997 | | | | |
| | $G_{0.5PM} = 0.72 + 0.62(G_L)$ | 0.51 | 0.29 MJ $m^{-2}$ | 114 |
| | $G_{PM} = 0.05 + 1.67(G_L)$ | 0.52 | 0.76 MJ $m^{-2}$ | 114 |
| 1996 and 1997 combined | | | | |
| | $G_{0.5PM} = 0.69 + 0.49(G_L)$ | 0.40 | 0.30 MJ $m^{-2}$ | 257 |
| | $G_{PM} = 0.06 + 1.58(G_L)$ | 0.46 | 0.86 MJ $m^{-2}$ | 257 |

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

Soil heat flux was not well estimated by either of the methods used (Fig. 9). But, 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. However that method was more biased, by 0.63 MJ $m^{-2}$ on average. The method using daily air temperatures also gave biased estimates (intercepts near zero, but slopes far from unity); and it tended to overestimate the larger heat fluxes, often by 2 MJ $m^{-2}$. This contributed only slightly to the larger scatter in daily PM estimates of $ET_R$ compared with the other two $ET_R$ methods. Computing daily PM estimates with soil heat flux set to zero did not reduce the standard error of estimate (SE) for regression against measured ET. But, it did reduce the positive bias slightly ($r^2$ = 0.90, intercept = 0.46, slope = 1.00, SE = 0.82 mm).

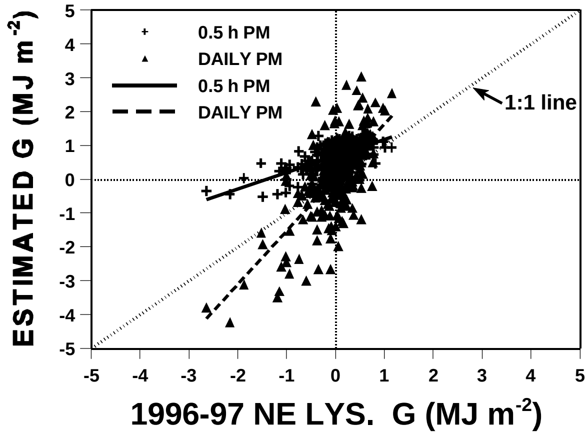


**Figure 9**. Comparison of soil heat flux, G, estimates with measured values for 1996-97.

## 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). Using curves of LAI and plant height fitted to measured data did not improve ET estimates, probably because of temporary lodging of the crop under our spray irrigation system.

Our sprinkler irrigation system caused two problems, the first of which was lodging of the crop. The second problem was that we often had to irrigate three times per week to keep the crop well-watered. This was because runoff was a problem if irrigation exceeded about 25 mm per day. Because lodging was usually a problem only when crop height exceeded 0.6 m, the first problem could be mitigated by harvesting earlier.

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.

## ACKNOWLEDGMENTS

Alfalfa lysimeter data acquisition, sensor maintenance, and net radiometer tests were done by Karen Copeland, Soil Scientist. Grass lysimeter and weather station sensor maintenance and data acquisition were done by Don Dusek, Agronomist. Brice Ruthardt, Biological Technician, maintained the weather station grass and took alfalfa yield samples. Jim Cresap, Biological Technician, sampled the alfalfa for plant height and LAI. All of these people, and the authors of this article, were assisted by numerous part time student workers and other staff, all employed by the USDA-ARS at Bushland. We are grateful for their efforts.

# REFERENCES


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

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

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

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

Doorenbos, J., and W.O. Pruitt. 1977. Guidelines for predicting crop water requirements. FAO Irrigation and Drainage Paper 24. Food and Agriculture Organization of the United Nations, Rome.

Dusek, D.A., T.A. Howell, A.D. Schneider, and K.S. Copeland. 1987. Bushland weighing lysimeter data acquisition systems for evapotranspiration research. ASAE Paper no. 87-2506.

Howell, T.A., S.R. Evett, A.D. Schneider, R.W. Todd, and J.A. Tolk. 1998. Evapotranspiration of irrigated fescue grass in a semi-arid environment. ASAE Paper no. 982117. ASAE Annual International Meeting, Orland, FL, July 12-16.

Jensen, M.E., D.C.N. Robb, and C.E. Franzoy. 1970. Scheduling irrigations using climate-crop-soil data. Proc. Am. Soc. Civ. Engr., J. Irrig. and Drain. Div. 96(IR1):25-38.

Jensen, M.E., R.D. Burman, and R.G. Allen (ed). 1990. Evapotranspiration and Irrigation Water Requirements. ASCE Manuals and Reports on Engineering Practices No. 70, ASCE, New York. 332 pp.

Marek, T., T. Howell, L. New, B. Bean, D. Dusek, and G.J. Michels, Jr. 1996. Texas North Plains PET Network. pp. 710-715 *In* C.R. Camp, E.J. Sadler, and R.E. Yoder (eds.) Proceedings of the International Conference on Evapotranspiration and Irrigation Scheduling. Nov. 3-6, 1996, San Antonio, Texas, U.S.A.

Steduto, P., A. Caliandro, P. Rubino, N. Ben Mechlia, M. Mamoudi, A. Martinez-Cob, M. Jose Faci, G. Rana, M. Mastrorilli, M. El Mourid, M. Karrou, R. Kanber, C. Kirda, D. El-Quosy, K. El-Askari, M. Ait Ali, D. Zareb, and R.L. Snyder. 1996. Penman-Monteith reference evapotranspiration estimates in the Mediterranean region. pp. 357-364 *In* C.R. Camp, E.J. Sadler, and R.E. Yoder (eds.) Proceedings of the International Conference on Evapotranspiration and Irrigation Scheduling. Nov. 3-6, 1996, San Antonio, Texas, U.S.A.

Wright, J.L. 1982. New evapotranspiration crop coefficients. J. Irrig. and Drain. Div. ASCE. 108(IR1):57-74.