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EVAPOTRANSPIRATION OF IRRIGATED FESCUE GRASS IN A SEMI-ARID ENVIRONMENT

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Summary: Evapotranspiration (ET) of subsurface irrigated fescue grass was measured with a 2.25 m^2 weighing lysimeter in a 0.3 ha weather station at Bushland, TX, during the latter half of 1995 through 1997. The1948 Penman combination equation performed as well as the newer FAO Penman-Monteith equation both in estimating the computed grass reference ET using weather data and in estimating the measured grass ET. Both equations underestimated the higher ET rates while overestimating the lower rates.

Keywords: advection, crop coefficient, lawn, net radiation, reference evapotranspiration

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EVAPOTRANSPIRATION OF IRRIGATED FESCUE GRASS IN A SEMI-ARID ENVIRONMENT [1]

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ABSTRACT

Evapotranspiration (ET) from a cool-season grass with a height of 0.12 m and a surface resistance of 70 s m^{-1} has become a standard reference surface as the basis for crop coefficients and for modeling water use from many crops. Although many data sets were used in developing and verifying this standard, few of them are subject to strong regional advection like that found in the Southern High Plains of the U.S. Our objectives were to measure water use from a fescue grass (*Festuca arundinacea* Schreb.), to determine if differences existed in computed reference grass ET from several widely used methods in this environment, and to examine methods for estimating irrigated fescue grass water use rates. ET of the subsurface irrigated fescue was measured at Bushland, TX, in the latter half of 1995 through 1997 using a weighing lysimeter (1.5 m by 1.5 m and 2.3 m deep) with an ET resolution exceeding 0.1 mm. The lysimeter was situated in an irrigated 0.3 ha grass weather station adjacent to other irrigated crops. Routine daily agricultural weather parameters (maximum and minimum air temperatures, mean daily barometric pressure, and mean daily dew point temperature in a cotton belt shelter at 1.5 m above the ground, wind speed at a 2-m height, and precipitation at 0.76 m height) were measured at the site together with specific data for the lysimeter – mass, net radiation, and soil heat flux. The lysimeter was manually vacuum drained periodically to remove excess water due to the slight over irrigation needed to sub moisture across the subsurface drip lines. The grass was regularly mowed to a 0.11 m height (weekly and even semiweekly if needed), and the clippings were bagged and removed. Nutrients were supplied mainly through the irrigation water and occasional surface applications to maintain strong vigor and health. Only days without significant rainfall (0.1 mm or less), drainage, mowing, or irrigation events were used in this analysis. After grass establishment in the fall of 1994, data collection began in late May of 1995. The Food and Agriculture Organization Penman-Monteith (FAO-PM) methods estimated net radiation well, but an assumption of zero soil heat flux was better than using the FAO-PM daily air temperature method. The data set contained a few days with ET rates exceeding 10 mm d^{-1}, but most of the midsummer ET rates were in the 6-10 mm d^{-1} range. Winter time ET rates varied, but often were in the 1-3 mm d^{-1} range. The 1948 Penman combination equation closely paralleled ET calculated with the more recent FAO-PM equation. The former FAO Penman equation over estimated the ET computed by the FAO-PM, while both the Priestley-Taylor and the Hargreaves and Samani equations under estimated the ET computed by the FAO-PM equation. The FAO-PM estimated ET was larger than that measured at low rates (mainly in the late fall, winter, and early spring) and tended to underestimate the ET for the higher rates (> 8 mm d^{-1}). Surprisingly, the 1948 Penman combination appeared to be slightly better correlated to the measurements and had a lower standard error of estimate. Both reference ET methods predicted higher grass ET rates than measured in the fall and spring. Crop coefficients, K_c, were computed for the FAO-PM reference ET and fitted with multi-term Fourier series using both time and growing degree scales. The K_c values were strongly correlated to the "decoupling coefficient," Ω, that was computed using the aerodynamic resistance from the FAO-PM and measured net radiation, soil heat flux, and evapotranspiration. The FAO-PM computed *"hypothetical"* grass reference ET accurately estimates irrigated fescue ET in mid to late summer in this environment , but it did not perform any better than the 1948 Penman combination equation.

Keywords: advection, crop coefficient, lawn, net radiation, reference evapotranspiration

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INTRODUCTION

Evapotranspiration (ET) from a well-watered grass has long been used as a reference value for estimating crop consumptive use. Jensen (1968) introduced the concept of the *"crop coefficient"* although previous ET methods had various *"crop factors"* such as the widely used method of Blaney and Criddle (1950 and 1962). Jensen defined the crop coefficient, K_c as

$$K_c = E_t / E_o \tag{1}$$

where E_t was the crop ET, and E_o was the *"potential"* or upper limit ET expected. He defined E_o as

> *"....the upper limit of evapotranspiration that occurs with a well-watered agricultural crop that has an aerodynamically rough surface such as alfalfa with 30-50 cm of top growth."* (Jensen, 1968)

And he further clarified that the *"fetch"* needed was at least 30 m and specifically included effects of regional advection or the *"oasis"* effect within his characterization of E_o. Doorenbos and Pruitt (1975 and 1977) further developed this concept for many crops for the Food and Agricultural Organization (FAO) of the United Nations as a method applicable world-wide, but they used a different basis for the *"reference crop evapotranspiration"* (one of the first mentions of the reference ET concept to our knowledge). They defined the crop coefficient similarly, but used the symbol kc (for K_c as in eqn. 1), and they specified the reference ET_o (for E_o in eqn. 1) as

> *".....the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water."* (Doorenbos and Pruitt, 1977)

Jensen et al. (1970 and 1971) demonstrated the use of these concepts for estimating crop ET for irrigation scheduling. Burman et al. (1980a,b) further developed the concept of using either of two crops, grass or alfalfa, as the *"reference crops."* In theory, any crop could be a reference crop although alfalfa and grass have distinct advantages. All of these works intended that the *"potential ET"* or *"reference ET"* would be a calculated value from any one of many methods based on local climate data. Many of the K_c values developed at Davis, CA, by Pruitt (Doorenbos and Pruitt, 1977) were based on simultaneous measurements of grass reference ET and crop ET with two lysimeters (one was a weighing lysimeter and the other was a floating type) (Pruitt et al., 1972). Few direct comparisons of reference crop ET for alfalfa and grass exist to our knowledge, although ET from both reference crops has been measured at Kimberly, ID, by Wright (1982 and 1996) but not simultaneously. All of these definitions of reference ET lead back to Penman's work (Penman, 1948, 1956, 1963) that defined *"potential evaporation"* as

> *"...the amount of water transpired in unit time by a short green crop, completely shading the ground, of uniform height and never short of water."* (Penman, 1956)

Businger (1956) and van Bavel (1966) attempted to clarify concepts of *"potential evaporation"* and inserted an adiabatic wind speed profile characterization for the empirical *wind function* employed in the Penman combination type equations. But these more theoretical *"wind functions"* have been reported to over predict potential evaporation in windy and dry humidity conditions (Rosenberg, 1969).

All of the Penman combination type equations assume indirectly that the surface resistance is zero and that the aerodynamic resistance is included within the wind function itself. Covey (1959), Rijtema (1965), and Monteith (1965) characterized this surface resistance in what now has become known as the *"single layer"* or *"big leaf"* model to better account for crop surface effects on aerodynamic properties and to include a surface resistance to the evaporation Penman combination equation. This equation has become widely known as the Penman-Monteith equation (Jensen et al., 1990) given as

$$ET_c = \frac{\Delta (R_n - G) + 86.4 \rho C_p (e_a - e_d) / r_a}{\lambda [\Delta + \gamma (1 + r_c / r_a]} \qquad (2)$$

where ET_c is the ET of the crop in mm d^{-1}, Δ is the slope of the saturated vapor pressure-temperature curve ($\partial e/\partial T$) in kPa °C^{-1}, R_n is net radiation in MJ m^{-2} d^{-1}, G is sensible heat flux into the soil in MJ m^{-2} d^{-1}, ρ is air density in kg m^{-3}, C_p is specific heat of moist air [1.013 kJ kg^{-1} °C^{-1}], e_a is the mean saturated vapor pressure in kPa, e_d is mean ambient vapor pressure in kPa, r_a is the aerodynamic resistance in s m^{-1}, r_c is the surface resistance to evaporation in s m^{-1}, λ is the latent heat of vaporization in MJ kg^{-1}, and γ is the psychrometric constant in kPa °C^{-1}. The resistance factors are explicitly defined for the crop of interest, and all other factors are measured (or computed) over or below the crop of interest. Jensen et al. (1990) proposed standardizing reference ET computations for grass at constant 0.12-m height and for alfalfa at a constant 0.50-m height based on Allen (1986) and Allen et al. (1989) and recommended using the Penman-Monteith combination equation for weekly, daily, or shorter periods with their formulated resistance factors and their procedures for estimating both R_n and G. They discussed problems with non representative climate data and that their R_n and G procedures may need to be used with some care in environments dissimilar to the ones that they had used for developing their recommended coefficients. We further caution readers that measuring R_n and G are in themselves no simple matter and any measurements of either R_n or G may contain significant instrument biases (Fritschen and Gay, 1979; or Allen et al., 1994b). Of course, errors in measuring G are insignificant on a longer time scale (> one day) in regards to ET and the energy balance of irrigated crops. Wright (1996) noted that the alfalfa R_n methods previously developed for Kimberly, ID, (Wright, 1982) worked well for clipped fescue grass, except for October, but only analyzed data for the April through October period. He indicated that a modified R_n methodology may be needed for grass.

The Penman-Monteith method outlined by Allen (1986) for grass was used by Martin and Gilley (1993) for developing the latest ET methods for USDA-NRCS (formerly the SCS, Soil Conservation Service). The only noticeable difference was that they used the grass albedo estimation method from Dong et al. (1992).

Allen et al. (1994 a and b) provided the recommended FAO and International Commission on Irrigation and Drainage (ICID) methodologies for estimating reference crop ET for grass (called ET_o hereafter). Their definitions of the *"hypothetical"* grass surface conditions were the following:

height	0.12 m
surface resistance	70 s m^{-1}
albedo	0.23
grass species	cool season type like perennial ryegrass (*Lolium perenne* L.) or tall fescue (*Festuca arundinacea* Schreb.)

Although not explicitly stated, they assumed an emissivity for the grass of 0.98. Further they used the common working assumption that Δ could be estimated at the mean ambient temperature (van Bavel, 1966). Their working equation made further simplifications for λ and ρ that may be unnecessary in this age of powerful personal computers, in our opinion, but these simplifications don't introduce any significant compromise in accuracy (at least for our conditions). Allen et al. (1994a) compared computed reference grass ET using this FAO-PM (FAO Penman-Monteith) equation with lysimetrically measured grass ET at Davis, CA, for a five-year period 1965 through 1969 and for various additional computation methods. For these daily data, the FAO-PM equation performed considerably better than the FAO Penman (Doorenbos and Pruitt, 1977), but only slightly better than the 1963 Penman equation (Penman, 1963). Using a variable r_c characterization based on solar radiation and/or vapor pressure deficit (VPD) did not improve the FAO-PM results. Allen et al. (1994b) reported hourly comparisons for a tall clipped fescue grass at Logan, UT, for 3 days in August in 1990. The FAO-PM equation slightly underestimated the measured grass ET by 3-4% for the whole day, but when the r_c value was corrected using a gradient Richardson number, which requires at least two levels of air temperature and wind speed measurements, better agreement was observed between the hourly measured and computed ET rates, particularly if R_n was computed as well. The daily summed hourly ET rates were reportedly within 5% if the *"the weather data were well behaved."* Rana et al. (1994) and Steduto et al. (1996) reported that the FAO-PM type equation underestimated grass ET in Italy and at several other Mediterranean sites.

McNaughton and Jarvis (1983) examined the Penman-Monteith equation as

$$\lambda E = \Omega \frac{\Delta (R_n - G)}{(\Delta + \gamma)} + (1 - \Omega) \frac{\rho C_p (e_a - e_d)}{\gamma r_c} \qquad (3)$$

where Ω is defined as a decoupling coefficient, and λE, R_n, and G are expressed in flux terms of W m^{-2}. The decoupling factor, Ω, is expressed as

$$\Omega = \left[1 + \frac{\gamma}{(\Delta + \gamma)} \frac{r_c}{r_a} \right]^{-1} \qquad (4)$$

The decoupling coefficient is explicitly linked to the saturation deficit (or vapor pressure deficit). They said that when Ω was small, vigorous turbulent mixing prevents the formulation of gradients. Conversely, when Ω was large (as they supposed for grass), the transpiration would be principally controlled by the net radiation and not as responsive to atmospheric conditions. They said

> *"...Ω sets the relative importance of the equilibrium term* [essentially the first term in the Penman-Monteith equation], *which is the transpiration rate that would be achieved if the surface were isolated from the bulk PBL* [planetary boundary layer] *by a very large resistance, and a term that represents the transpiration rate that would occur if the saturation deficit in the outer layer were imposed at the surface with no local adjustment."* (McNaughton and Jarvis, 1983)

Steduto et al. (1996) reported that $r_c\ r_a^{-1}$ was more variable than that assumed by the FAO-PM equations for grass. Rana et al. (1994) showed that significant improvement could be obtained in estimating grass ET by introducing a different r_c relationship for grass. Later, Rana et al. (1996) used this relationship through a factor directly proportional to Ω, the decoupling coefficient, and fashioned it as a crop coefficient (K_c used hereafter).

The purpose of this work is to examine the suitability of the FAO-PM reference ET equations and methods for daily climate data for estimating reference grass ET in an advective semi-arid environment at Bushland, TX, in the U.S. Southern High Plains. Then, we want to examine its performance in predicting actual measured irrigated fescue grass ET throughout several seasons and to determine the degree of coupling between irrigated grass ET and the atmosphere and to determine the degree of association that exists between the decoupling coefficient, Ω, and the crop coefficient for irrigated fescue grass.

METHODS AND MATERIALS

This study was conducted at the USDA-ARS Conservation and Production Research Laboratory at Bushland, Texas (lat. 35°11' N; long. 102°06'; 1170 m elevation MSL). A weighing lysimeter (Schneider et al., 1998), 1.5 m by 1.5 m and 2.3 m deep containing a monolith of Pullman clay loam (*Torrertic Paleustolls*), was used to measure ET. It was situated in a 0.3 ha weather station (fetch from 27 to 37 m in the predominate wind direction). Dusek et al. (1987) provide additional details about the weather station, but the station plot area was expanded when the lysimeter was installed in 1994. The station siting is not ideal, and the fetch for standard weather measurements at 2 m is marginal. But this is typical for many agricultural weather stations, and far above average for many research weather stations sites. For comparison, Steduto et al. (1996) reported even smaller sites (but the one in Morocco was 0.7 ha), and the Kimberly, ID, weather station was reported as 0.16 ha (45 m by 36 m) by Wright (1988). Heilman and Brittin (1989) reported significant boundary-layer adjustment occurred within the first 15 m over a smooth Bermuda grass [*Cynodon dactylon* (L.) Pers.]surface as it transitioned from a rougher cotton (*Gossypium hirsutum* L.) field, especially when the Bowen ratio was small as would be expected for the case of an irrigated grass in our situation. The weather station is surrounded by irrigated crops with 8 ha of irrigated alfalfa (*Medicago sativa* L.) immediately to the west and south (the predominate wind direction), and rotations of irrigated soybean (*Glycine max* (L.) Merr.) and corn (*Zea mays* L.) in a 0.6 ha microirrigated set of plots to the south and in a 5.7 ha center pivot plot area to the north and east during this study period. We are convinced that the measured ET rates are valid even with the small fetch, but it is quite possible that the 2-m wind speeds and perhaps the 1.5-m temperatures have, on occasion, been outside the internal boundary layer.

Tall fescue grass (*Festuca arundinacea* Shreb.) was commercially hydro-mulched in the late fall of 1994 on the weather station plot after the lysimeter and subsurface drip irrigation system installation was completed. The seed was a turf blend named Emerald III (Sharp Bros. Seed Co.), which consisted of equal fractions of three tall fescue varieties – Jaguar II, Mustang, and Rebel II. The grass did not emerge as quickly in the fall of 1994 as we had hoped. Consequently, it did not reach full cover with vigorous growth until mid spring in 1995. We are only reporting and using data measured after June 23, 1995, (DOY 174) through December of 1997. Figure 1 shows the lysimeter with a view to the east (the shortest fetch side), and Fig. 2 shows a detail view of the grass in 1997 illustrating excellent growth inside and outside the lysimeter. The grass was mowed regularly with a rotary mower, and the clippings were bagged and removed. The grass height was 100-110 mm after mowing and varied from 140 to 200 mm before mowing. Typically the tallest height was just before the first spring mowing, and then the mowing height was lower (about 50 to 70 mm) to remove dead vegetation from the winter. During peak growth periods, the grass was mowed as frequently as every four to five days.

Table 1 lists the instruments used to measure the various parameters. All sensors were measured at 6 s intervals and averaged for 30-min. and daily (24-h) time periods with a Campbell Scientific CR-7X data logger powered by 120 VAC. The lysimeter was a commercial deck scale with four load beams. The load beams were excited and measured by the same data logger used in the weather station. The lysimeter full-range precision is at least as good as ± 0.1 mm (Schneider et al., 1998), and we believe that short-term (hourly) precision may approach 0.05 mm. The lysimeter air gap between the inner and outer walls was only 10 mm, but when the wall thickness was added, the "mid-wall" lysimeter area would be almost 8% larger than the lysimeter inside area. Typically, we have adjusted the measured ET for our larger lysimeters (for taller crops) to this mid-wall area (Howell et al., 1997). But this lysimeter has a freeboard wall height of 0.10-0.11 m and an additional effective height of 10 mm for the rubber rain seal. So, this is about the same height as the mowed grass, and few blades were observed to lap in or to lap over the inside lysimeter wall (Fig. 2). Therefore, we decided not to correct the measured lysimeter mass values to the mid-wall area for grass in this case.

The grass lysimeter net radiometer (a REBS Q7) was corrected to match the net radiation measured using a REBS Q5.5 net radiometer that our group more routinely uses. The correction equation that we used was RnQ5.5 = RnQ7*1.164 + 0.131. Soil heat flux (REBS HFT-1) was measured with four plates buried at 0.05 m and corrected to the soil surface using soil temperature measured at 0.01 and 0.04 m by four pairs of thermocouples.

The irrigation system used 1.9 L h^{-1} Geoflow turbulent flow emitters spaced every 0.46 m along the lateral and the laterals were spaced 0.46 m apart in the weather station plot. The emitters were in 14 mm ID laterals and located 0.15 m deep. The lysimeter had a dense network of 3.8 L h^{-1} emitters (64 arranged in a 0.19-m square grid) that permitted 25 mm of water to be applied in 15 min. Fertilizers (both N and P) were applied through the irrigation water. The irrigations were applied regularly to maintain vigorous grass growth.

Daily reference ET_o was computed with a Penman-Monteith equation exactly as outlined by Allen et al. (1994b) (eqn. 1), and all parameters were computed with the equations contained therein. The daily input data included the date, day of year, maximum air temperature, minimum air temperature, mean daily dew point temperature (Howell and Dusek, 1995), mean 2-m wind speed, daily solar radiation, mean daily barometric pressure, and daily precipitation. The lysimeter ET data included ET, net radiation, mean daily soil heat flux plate measurements (four), mean daily soil temperatures at the 0.10 and 0.40 m depths (four each), daily lysimeter drainage (from manual recordings of pumping volumes), and daily lysimeter irrigation amounts. ET data were screened to use only days without mowing, without appreciable rainfall (<0.1 mm), without drainage, and without irrigation. Usually, mowing and many of the irrigation and drainage days coincided. Winter days with snow and/or suspicions of drifting snow were also removed. Mean ambient vapor pressure, e_d, was computed from the mean daily dew point temperature. Daily saturated vapor pressure was computed as the mean saturated vapor pressure at the maximum and minimum air temperatures. Mean daily barometric pressure was an input parameter rather than assuming a constant based on elevation. λ was allowed to vary with mean temperature. The assumed net radiation constants (see Allen et al., 1994b for details) were

a_c 1.35
b_c -0.35
α 0.23
a_1 0.34
b_1 -0.14
R_{so} = (0.75 + 2E-5*1170)*R_a, where R_{so} is clear day solar radiation and R_a is extraterrestrial radiation and the 1170 represents the elevation in m at Bushland

Daily soil heat flux, G, was estimated by eqn. 1.56 in Allen et al. (1994b). The aerodynamic resistance, r_a, was estimated using the following parameters from Allen et al. (1994b):

h_c 0.12 m
d = 2 h_c / 3
z_{om} = 0.123 h_c
z_{oh} = 0.0123 h_c
z_m 2 m
z_h 1.5 m

The surface canopy resistance was assumed to be 70 s m^{-1} (Allen et al., 1994b).

Several *"potential ET"* and *"reference ET"* equations were used to compute ET with the same weather data (all 922 days) for comparison purposes. Exact equations are found in Howell et al. (1997), but we substituted the Hargreaves and Samani (1985) equation that used daily solar radiation and mean daily temperature for the Jensen-Haise equation used in that previous study. The Penman wind functions and matching saturated vapor pressure methods are outlined by Howell et al. (1997) and found in Table

1.56 in Jensen et al. (1990). For discussion, we named these as Pen-48 (Penman, 1948; Penman, 1963), FAO-Pen (Doorenbos and Pruitt, 1977), PT (Priestley and Taylor, 1972), and the HS (Hargreaves and Samani, 1985). All these equations were intended to represent irrigated cool-season grass like the FAO-PM (Allen et al., 1994b), except the PT which has been applied to any crop in *"non advective"* conditions (a category in which Bushland is certainly not found). The PT equation is widely used as a measure of the *"equilibrium ET"* and has interest for other reasons.

The surface resistance to evaporation, r_c, was back computed using eqn. 2 with measured R_n, G, e_a, e_d, and T (mean temperature) together with the computed r_a (Allen et al., 1994b). Then, Ω was computed by eqn. 4 using this derived r_c value with the estimated r_a.

The grass crop coefficient (K_c) was computed by eqn. 1 using the measured grass ET and the computed reference ET (FAO-PM). Crop coefficients were fit to both time (DOY) and cumulative growing degree day (CGDD) scales using multi-term Fourier series using PROC REG of SAS (SAS/STAT, 1987). Growing degree days (GDD) for fescue grass were based on a base temperature of 0°C (Frank et al., 1985) and assuming an upper cutoff temperature of 30°C. This is the standard GDD method widely used for corn and for our North Plains weather network (Marek et al., 1996). GDD methods are not standardized and are difficult to compare. Frank et al. (1985) did not start summing GDDs until mid-March at Mandan, ND. For the 1995-97 years, we could not establish a reliable starting date, so our GDDs were summed from January 1 of each year. In all these years, GDDs increased even from January 1 during the winter. Fescue will freeze back here, but it can begin to regrow and freeze back several times during the winter.

RESULTS AND DISCUSSION

The grass was seeded late in 1994 and did not establish a vigorous stand until the spring of 1995. By mid May it was growing actively and had reached complete cover. Data collection was started and data quality appeared satisfactory after 23 June (DOY 174) in 1995. Some problems were noticed in the plot that included incomplete wetting across the drip lines and a rust (*Puccinia* spp.) infestation in the 1995 fall. The rust was treated with a fungicide [Tilt (Ciba), a.i. Propiconazole: 1-[[2-(2,4-dichloronphenyl)-4-propyl-1,3-dioxoloian-2-yl]methyl]-1*H*-1,2,4-triazole] applied at 58 µL (a.i.) m^{-2} that effectively eliminated the problem. Plant pathogens have been shown to reduce water uptake in grass (Nus and Hodges, 1986), but we felt this infestation did not significantly change the water use patterns. Some over-watering was needed to fully wet all the areas between the lines in all years. But the grass grew well and maintained excellent quality throughout 1995 to current times. Figures 1&2 illustrate the excellent grass condition.

In early April of 1997, a lightning strike damaged one of the load beams in the scale. The enclosure top had to be removed to provide access to lift and remove the soil monolith and scale for repairs. About 0.6 to 0.8 m of grass sod immediately surrounding the lysimeter was removed during this process as well as the grass sod on the lysimeter so instruments (soil heat flux plates, thermocouples, etc.) could be replaced as well. A large crane that could span the distance from the east field edge (see Fig. 1) was used to lift the soil container and scale to avoid damaging the grass plot and irrigation system. The scale was repaired and reinstalled within three days with the same crane. Grass sod was cut from the plot edges to replace the sod on and around the lysimeter. The lysimeter was recalibrated and functioning again by early May, but grass growth had not fully recovered until early June so that the data could be reliably used.

Environmental conditions during the data collection period (mid 1995 through 1997) were typical for the Southern High Plains. Table 2 provides a climatic summary for this period. In Dec. 1995 and 1996, T_{max} was above normal and T_{min} was somewhat below normal in Mar. of 1996 and 1997. Wind speeds and solar irradiance were consistent with longer-term means. The high mean monthly wind speeds (Table 2) are typical and show the normally higher spring (Mar. through May) winds. Cumulative GDD curves for all three years were remarkably similar. Season sums of GDDs were 5068, 5207, and 4931 °C-d in the three years 1995, 1996, 1997, respectively.

All weather data are screened for quality with procedures similar to Allen (1996). Practically all measurements are duplicated either within the weather station or on adjoining larger lysimeter fields. Table 2 indicates that mean dew point was about 3-4°C greater than T_{min} in most of the latter part of 1995 and into 1996 until mid summer. The monthly mean precipitation/ET_o ratio would seldom be expected to approach a value of 1.0 (maybe only during winter), and routinely it is below 0.5. The aridity pattern at Bushland based on Table 2, appears quite similar to that in Allen (1996) for Kimberly, ID. But, we do not think that Kimberly, ID, experiences the extreme advective spring events with the frequency or extent they occur at Bushland, TX (that's one reason there is a wind energy research program at Bushland too). The two counties south and west (Randall and Deaf Smith) in the predominate wind path to Bushland, TX, have more than 94,000 ha of irrigated land, but, like most of the Southern High Plains, irrigated land is dispersed amongst dryland fields and rangelands that are not irrigated.

Reference ET Equation Comparisons

Table 3 presents a summary of the linear regression results comparing the various reference ET methods with the FAO-PM reference ET method for the measured Bushland climatic data. It is immediately obvious that the Pen-48 equation performs as well as the FAO-PM in this extreme environment. Its mean daily computed ratio is almost identical to that for the FAO-PM equation. The regression slope is less than the ideal of 1.0 because it has a slight positive intercept bias (0.23 mm d^{-1}). The FAO-Pen overestimated the computed grass reference ET by the newer FAO-PM, but this has been widely known (Jensen et al., 1990), and is the reason FAO was interested in revising its reference ET method. But the FAO-Pen has the highest correlation coefficient (r^2 was 0.97), and very likely with the proper correction factors (Doorenbos and Pruitt, 1977) for the Bushland wind and humidity regimes, it would perform as well as the Pen-48 equation. Both the PT and HS methods underestimated the computed grass reference ET by the FAO-PM method, both had lower coefficients of determination, slopes and mean ratios much lower than 1.0, both had lower standard deviations (they did not capture the range of variability as well), but they did have minimum offset biases (intercepts different from 0.0).

Comparison of Measured Net Radiation and Soil Heat Flux with FAO-PM Computed Values

The corrected measured net radiation (from the REBS Q7 to a REBS Q5.5 net radiometer) tracked that computed by the standard methods in FAO-PM well, except when the measured daily values were small (<1.2 MJ m^{-2} d^{-1}). For these cases, the FAO-PM computed R_n remained at about 3 to 4 MJ m^{-2} d^{-1} while the measurements continued to go further negative to -2 to -3 MJ m^{-2} d^{-1}. When we deleted any measured data points smaller than 1.23 MJ m^{-2} d^{-1}, the resulting linear regression was $R_{nFAO\text{-}PM} = 0.49 + 0.916*R_{nQ5.5}$, with $S_{y/x} = 1.01$ MJ m^{-2} d^{-1} and $r^2 = 0.953$. We feel this agreement is quite acceptable, and well within the errors possible in measuring R_n. We are making some albedo measurements currently, but we don't know as yet if an albedo equation such as that from Dong et al. (1992) would appreciably improve estimates of R_n for our fescue grass.

The FAO-PM daily soil heat flux method greatly overestimated the dynamic nature of the measured soil heat flux under our fescue grass and for our Pullman soil. It did not appear to be biased (intercept was near 0.0), but it added random noise that didn't appear useful. For our data, an assumption of zero soil heat flux would agree better with our measured daily soil heat flux range from -1 to 1 MJ m^{-2} d^{-1}. The linear regression result was $G_{FAO\text{-}PM} = 0.07 + 2.609*G_{meas}$ with $S_{y/x} = 1.31$ MJ m^{-2} d^{-1} and $r^2 = 0.188$.

Comparison of Measured Grass ET with Computed FAO-PM Grass Reference ET

Daily grass ET and computed reference ETo rates are illustrated in Fig. 3 for the extent of this study period. Extreme ET and ET_o rates approached 12 mm d^{-1} (but not on the same days unfortunately). Wright (1996) and Allen et al. (1994a) showed few grass ET rates exceeding 9-10 mm d^{-1} for Kimberly, ID, or Davis, CA, respectively. Steduto et al. (1996) likewise did not report any measured grass ET rates more than 10 mm d^{-1}, and neither did Rana et al. (1994). Of important note is the good agreement between the measured ET and FAO-PM estimated ET_o during mid season and the over estimation of grass ET by FAO-PM during the late fall, winter, and into into the spring. This is not surprising since the critical assumptions embodied in the *"hypothetical"* FAO-PM reference grass (α, r_c, and ϵ) are unrealistic for actual grass during this period. The grass may not be in a condition to transpire at a reference condition although it may still appear *"vigorous."*

The irrigated fescue ET was compared with calculated reference ET_o for days without rain, mowing, irrigation, or drainage that could introduce water balance uncertainties (Fig. 4). The overall regression for these data indicated a tendency to over estimate grass ET for low rates and to underestimate ET for high ET rates by the FAO-PM equation. The linear regression results are summarized by years and composite data in Table 4. Each year had differing results, but all years exhibited this trend. Qian et al. (1996) reported similar observations in Kansas. Although, the $S_{y/x}$ values for 1995, 1997,and the composite data were similar to that shown by Allen et al. (1994a) for grass at Davis, CA, and that presented for perennial ryegrass (*Lolium perenne* L. 'Barvestra') by Rana et al. (1994), the average ratio was exaggerated by the large numbers of higher ET during the non-summer growing conditions when the FAO-PM computed ET rates were generally larger than the measured data. Our scatter was not too unlike that reported by Rana et al. (1994) at Rutigliano, Italy. When we forced the regression through the origin (Table 4), the resulting slope was 1.06. Since the Pen-48 equation appeared to be comparable in performance to the FAO-PM equation, we compared it to the measured irrigated fescue ET (Fig. 5). Surprisingly to us, it actually had a higher coefficient of determination ($r^2 = 0.79$) and had a smaller standard error of the estimate ($S_{y/x} = 0.95$ mm d^{-1}). Wright (1996) used a Penman equation that predicted grass ET well at Kimberly, ID, with a self-derived wind function for the April through October season. We examined this April through October period separately (Table 4), but it did not significantly alter our results for the FAO-PM equation.

Fescue Grass Crop Coefficients

Grass reference ET information is widely used in many locations in the U.S. to advise urban irrigators about lawn irrigation requirements (Feldhake et al., 1983; Devitt et al., 1992; Qian et al., 1996). One of our justifications for choosing the FAO-PM grass reference equation as the basis for our North Plains PET network (Marek et al., 1997) was to provide local information to urban water users. K_c factors for different grass species are used in this network to estimate lawn water needs for several popular type grass species like those given in Devitt et al. (1992). Since fescue grass ET, at Bushland, appeared to differ substantially from the FAO-PM estimates at different times of the year, we computed grass K_c values to better predict actual grass ET in this environment.

Figure 6 shows the computed crop coefficient, K_c, plotted on a time scale, and Fig. 7 shows the same data plotted on a cumulative growing degree, CGDD, scale. Jensen et al. (1990) showed close correspondence between measured and computed grass reference ET by the Penman-Monteith equation at almost all locations across the growing year (and hence a K_c always near 1.0). Wright (1996) also showed good agreement for April through October between estimated reference ET with a wind function derived for Kimberly, ID, and actual grass ET (K_c would be 1.0). Obviously, winter months are not always going to have conditions favorable for reference ET grass growth conditions at Bushland and many other temperate climates. Devitt (1992) showed a similar seasonal trend for K_c of turfgrass sites in Las Vegas, NV, when using the Penman (1963) equation from Jensen et al. (1990) to estimate reference

ET. The CGDD time scale compresses the cooler months and expands the warmer more active growth time period (April through September). The curves shown in Figs. 6 and 7 were fit with multiple term Fourier series, and the specific coefficients are given in Table 5. Polynomial equations fit almost as well, but the Fourier series fits can be flatter (like the CGDD curve) and not as "rounded." It is clear that the actual fescue grass surface resistance must have been considerably higher than that assumed in the FAO-PM during the winter. It may be related to the lower radiation at that time of year or even the shorter photoperiod, but we suspect it is more likely related to effective leaf area and perhaps other morphological or physiological factors (Frank et al., 1985) or even specific cultivar (Bowman and Macaulay, 1991) differences. Crop coefficient curves based on the Pen-48 grass reference ET equation did not differ appreciably from those given here using the FAO-PM equation.

Relationship Between the Decoupling Coefficient and the Crop Coefficient

When the decoupling coefficient, Ω, is large, the evaporation is controlled by the equilibrium evaporation rate, which is generally thought to be influenced more by net radiation than by the imposed boundary layer saturation deficit. Both canopy and aerodynamic resistance affect Ω in differing mechanisms and likewise affect evaporation. The control of evaporation from leaf, canopy, boundary layer, and larger regional scale atmospheric dynamics are often challenging to identify (Jarvis and McNaughton, 1986; and McNaughton and Jarvis, 1991). We examined several possibilities for explaining why our r_c values are higher in the spring and late fall, but we did not find much direct association to either vapor pressure deficit or solar radiation. This is not in itself surprising as McNaughton and Jarvis (1991) argued that canopy control of evaporation depended more strongly in most situations on the leaf saturation deficit than on the atmospheric saturation deficit.

The decoupling coefficient, Ω, was strongly related to K_c, as implied by Rana et al. (1996) (Fig. 8). This observation is almost self-fulfilling since K_c must depend strongly on r_c. In the Southern High Plains, *"reference evaporative"* conditions are almost impossible to isolate from larger scale advection regardless of fetch. This region is not unique in that regard as much of the western Great Plains experiences such conditions. The degree of this advection is illustrated by a fairly strong association between vapor pressure deficit and net radiation (Fig. 9). The relationship is not presented as being unique, because many sites may exhibit such a relationship when air temperatures and vapor VPDs increase as net radiations increases. Figure 9 does illustrate how many large mean daily VPD days occur (the upper 25% or so of the data points that fall way above the regression line) at Bushland. Obviously, in such locations one cannot expect equilibrium or radiation-temperature based methods to be reliable. Figure 9 demonstrates why the PT (Priestley and Taylor, 1972) and HS (Hargreaves and Samani, 1982) will often under predict grass reference ET in the Southern High Plains, although they can be highly reliable in other locations with less advection.

SUMMARY AND CONCLUSIONS

Evapotranspiration from an irrigated fescue turf was measured for daily periods in a semi-arid, advective environment at Bushland, TX, in the Southern High Plains. The FAO-PM procedures (Allen et al., 1994b) represented the measured net radiation reasonably well. In this case, the assumption of zero daily soil heat flux for grass seems appropriate and generally less erratic than the proposed method based on daily air temperatures changes, although it didn’t improve our relationships between measured grass ET and computed reference ET much. The Pen-48 (Penman, 1948; Penman, 1963) combination method estimated reference ET as characterized by the FAO-PM equation well, and it, in fact, better represented irrigated fescue grass ET than did the FAO-PM at Bushland. We are planning to attempt to investigate the half-hourly and hourly data in the future with the notion that perhaps these data can improve the

FAO-PM results here where winds speeds and relative humidity trends often don't follow those *"well behaved weather data"* that Allen et al. (1994b) mentioned.

Since we found departure in actual irrigated grass ET (that should have been in a state to meet the reference ET definitions) here from that predicted by the FAO-PM equation or the Pen-48 equation, we developed K_c curves for irrigated fescue grass. The curves based on a GDD scale contained a better defined "maximum" K_c, near to a value of 1.0 to match the FAO-PM estimates. Winter K_c values were about 0.4.

Surface resistance to evaporation for fescue was back calculated from the measured ET, R_n, and associated weather parameters and used to determine the degree of coupling between the canopy and the imposed evaporative conditions. This decoupling coefficient was strongly related to the derived K_c values through the computed r_c values. Although we haven't investigated them yet, the procedures for estimating r_c and its association to r_a evaluated by Rana et al. (1994) might improve our estimate of irrigated fescue water use rates.

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Table 1. Instruments used in the study.

Instrument	Manufacturer [1/]	Deployment
Lysimeter scale	Weigh-Tronic	-2.5 m
Pyranometer	Eppley PSP	2 m
Anemometer	Met One 014A	2 m
Temp./RH	Rotronics MP100	1.5 m in CB [2/] shelter
Rainfall	Sierra Misco 2500E	1 m
Barometric pressure	YSI 2014	in CB shelter
Net radiometer	REBS Q7	1 m
Soil heat flux plates	REBS HFT-1	-50 mm
Soil thermometer	Cu-Co Thermocouples	10 and 40 mm
Data logger	Campbell CR-7X	

[1/] 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.
[2/] CB is Cotton Belt.

Table 2. Summary of mean monthly weather data for Bushland, TX, during the study.

	T_{max} °C	T_{min} °C	T_{dew} °C	U_{2g} m s^{-1}	R_s MJ m^{-2} d^{-1}
1995					
July	32.6	17.8	13.4	3.4	26.5
Aug	31.8	18.0	15.7	4.1	22.4
Sept	26.1	4.5	11.8	3.8	16.8
Oct	22.7	4.6	2.5	4.3	16.9
Nov	17.6	-0.9	-1.7	4.6	12.0
Dec	10.1	-4.1	-5.3	4.0	9.3
1996					
Jan	10.6	-8.2	-8.9	5.1	11.6
Feb	14.1	-4.0	-6.6	4.6	14.8
Mar	15.9	-4.0	-7.0	4.9	19.6
Apr	21.8	3.2	-2.9	5.4	23.8
May	29.6	12.0	7.4	5.2	25.0
Jun	31.3	15.6	14.1	3.9	25.1
July	30.8	14.5	16.8	3.8	23.8
Aug	29.1	15.6	18.2	3.4	20.8
Sept	25.1	12.5	13.0	3.6	18.9
Oct	21.5	6.2	4.5	4.4	14.4
Nov	15.5	0.1	-0.3	4.5	11.6
Dec	12.1	-3.7	-6.7	4.8	10.8
1997					
Jan	8.8	-4.5	-6.3	4.5	9.9
Feb	10.3	-2.7	-3.0	4.5	10.8
Mar	19.3	-0.1	-3.6	5.0	20.3
Apr	16.0	2.2	1.8	4.8	18.6
May	23.9	10.1	9.4	4.3	23.6
Jun	29.5	15.1	13.9	4.1	24.6
July	32.2	17.6	15.0	3.9	25.5
Aug	30.3	16.9	16.3	3.3	21.4
Sept	28.6	14.8	13.5	3.6	17.5
Oct	22.0	6.7	5.6	4.6	15.7
Nov	13.1	-0.8	-1.8	4.0	10.7
Dec	6.8	-4.3	-4.2	4.5	9.1

Table 3. Summary of linear regressions between the FAO-PM equation estimates of grass ET (independent variable) and grass reference ET estimated by other equations for 923 days (June 23, 1995 through December 31, 1997) at Bushland, TX.

Equation	Mean mm d^{-1}	Std. Dev. mm d^{-1}	Intercept mm d^{-1}	Slope -----	r^2 -----	Mean Ratio† -----
FAO-PM	4.57	2.43	--------	--------	--------	--------
Pen-48	4.58	2.33	0.228	0.949	0.949	1.013
PT	3.01	2.01	0.059	0.650	0.602	0.661
FAO-Pen	5.51	2.77	0.290	1.139	0.966	1.219
HS	3.35	2.01	-0.014	0.736	0.786	0.714

† Mean of the daily ratios of the model estimated ET to the FAO-PM value (i.e. $\text{Pen-48}_i / \text{FAO-PM}_i$ for day i)

Table 4. Summary of linear regressions between computed daily grass reference ET using the FAO-PM equation and irrigated fescue ET (independent variable) measured by a weighing lysimeter at Bushland, TX.

Season	No. of Obs.	Intercept mm d^{-1}	Slope -------	Std. Error of Slope --------	Std. Error of Estimate mm d^{-1}	r^2 ------
1995	117	1.42	0.804	0.032	0.926	0.842
1996	229	2.41	0.614	0.035	1.269	0.578
1997	180	1.70	0.715	0.024	1.696	0.836
Composite	526	1.96	0.692	0.019	1.079	0.723
Composite	526	0.0 (forced)	1.055	0.015	1.542	0.432
April through Oct.	262	1.38	0.765	0.031	1.025	0.704

Table 5. Crop coefficient Fourier series coefficients.

Parameter	DOY Scale	GDD Scale
B(0)	0.788	1.296
B(1)	-0.202	-0.793
B(2)	-0.309	9.080E-2
B(3)	-1.782E-2	-0.167
B(4)	-2.258E-2	-0.944
B(5)	---	0.355
B(6)	---	-0.047
r^2	0.786	0.766
Mean Square Error	1.905E-2	2.095E-2

L_d = 365 for DOY and L_{GDD} = 11000 for CGDD; L is the period.
K_c = B(0)+B(1)*Sin(X)+B(2)*Cos(X)+B(3)*Sin(2*X)+B(4)*Cos(2*X)+B(5)*Sin(3*X)+ B(6)*Cos(3*X)
X = 2*π*DOY/L_d for DOY and X = 2*π*CGDD/L_{GDD} for the CGDD scale

Figure 1. View of the grass lysimeter (directly under the net radiometer) looking to the east (photo taken on Oct. 10, 1997). The outline of the lysimeter is faintly discernable, the white PVC conduit fitting in the lower left of the photo is near the northwest corner of the lysimeter, and the gray material (duct tape) patch on the rubber rain seal is visible in the lower right (on the southwest corner) .

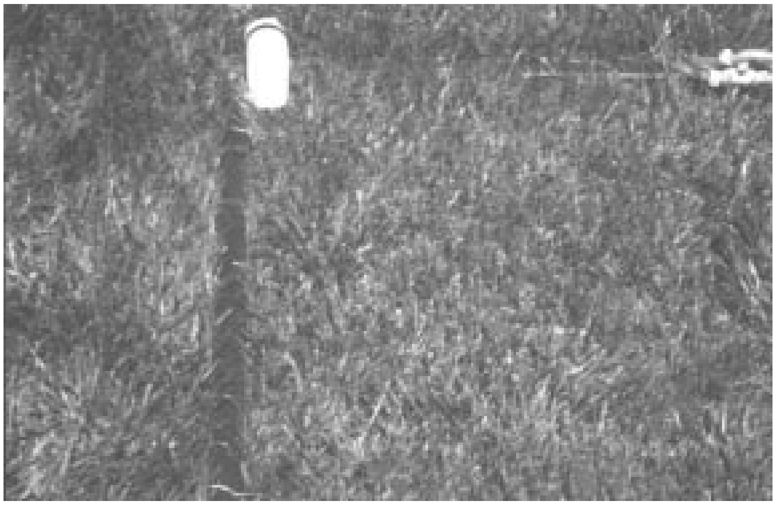

Figure 2. Closeup view of the northwest lysimeter corner (photo taken on Oct. 15, 1997, same day as Fig. 1) showing minimum overlap of the grass blades in or out of the lysimeter. The total wall thickness (both walls and the air gap) is approximately 30 mm.

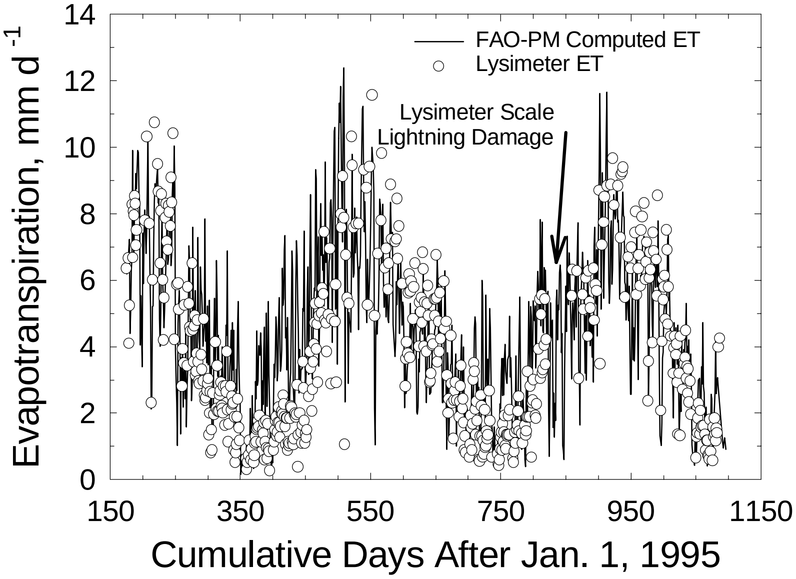

Figure 3. Daily computed grass reference ET using the FAO-PM equation and measured grass ET from June 23, 1995, through December 31, 1997.

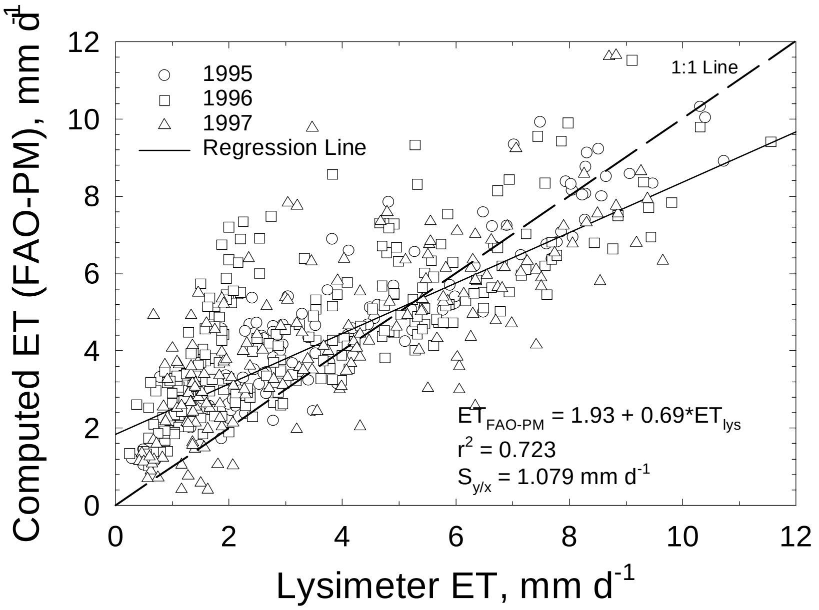

Figure 4. Computed grass reference ET using the FAO-PM equation compared

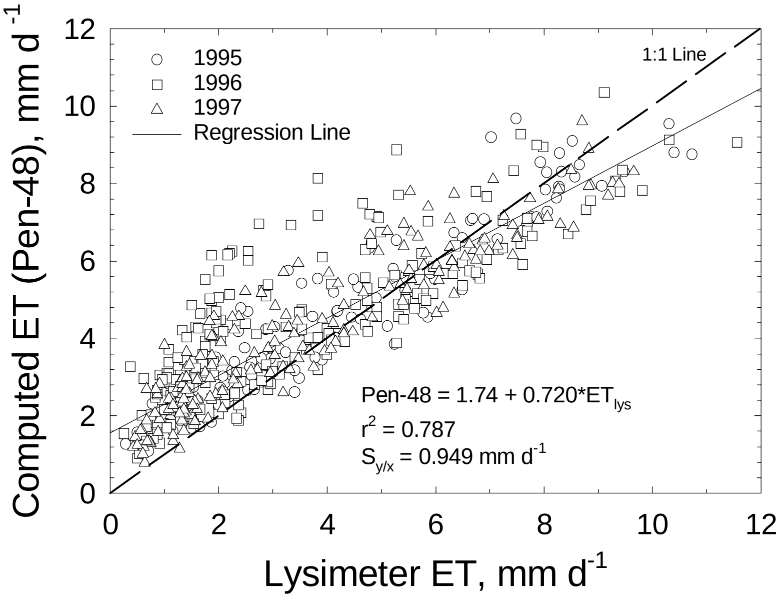

Figure 5. Computed grass reference ET using the Pen-48 equation compared with measured ET from irrigated fescue grass at Bushland, TX, from late June of 1996 through December of 1997.

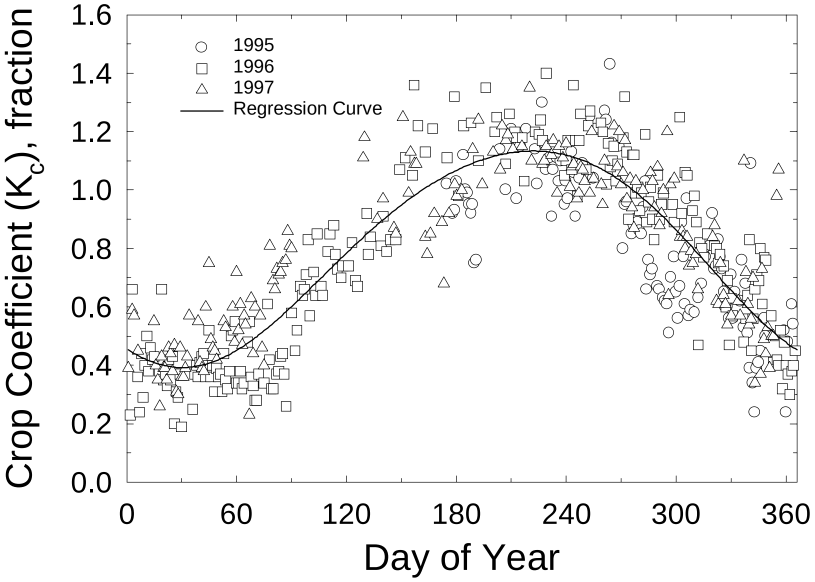

Figure 6. Crop coefficient curve for irrigated fescue grass at Bushland, TX.

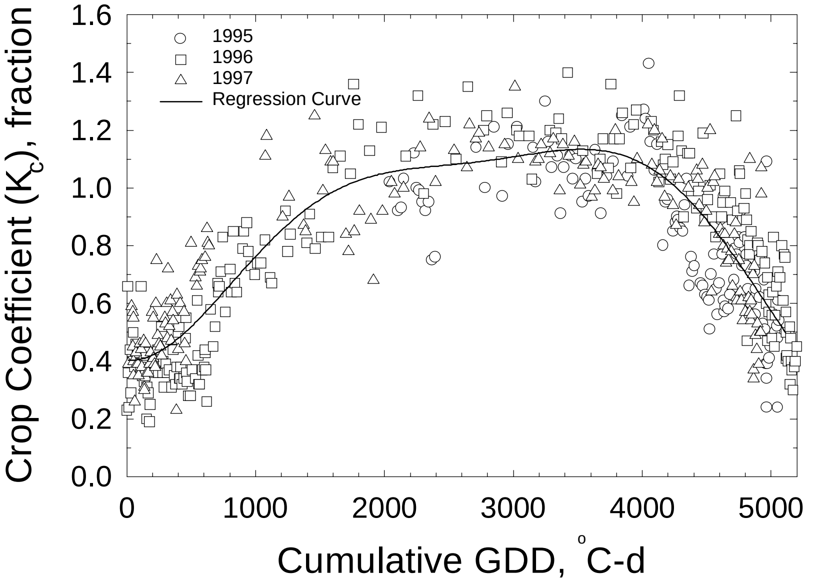

Figure 7. Crop coefficient for irrigated fescue grass at Bushland, TX, on a growing degree scale (T_{base} = 0°C and T_{upper} = 30°C).

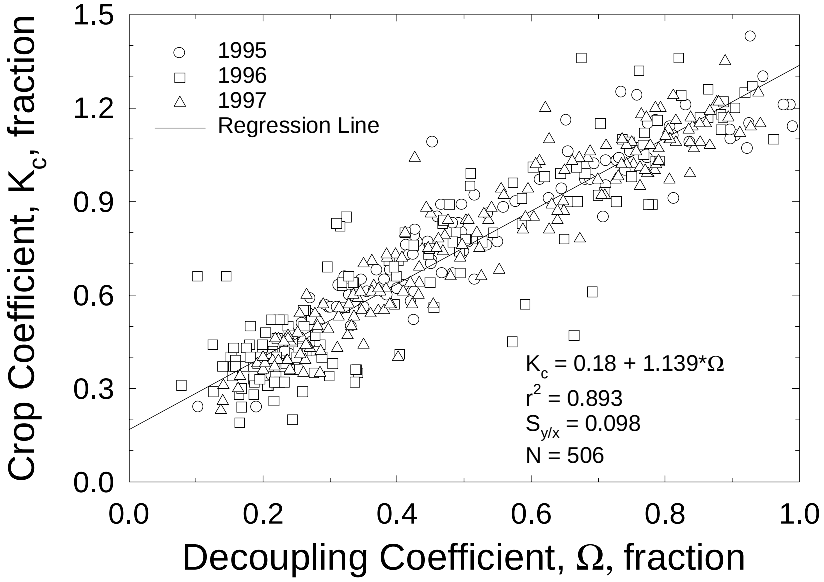

Figure 8. Relationship between the grass crop coefficient, K_c, and the decoupling coefficient, Ω.

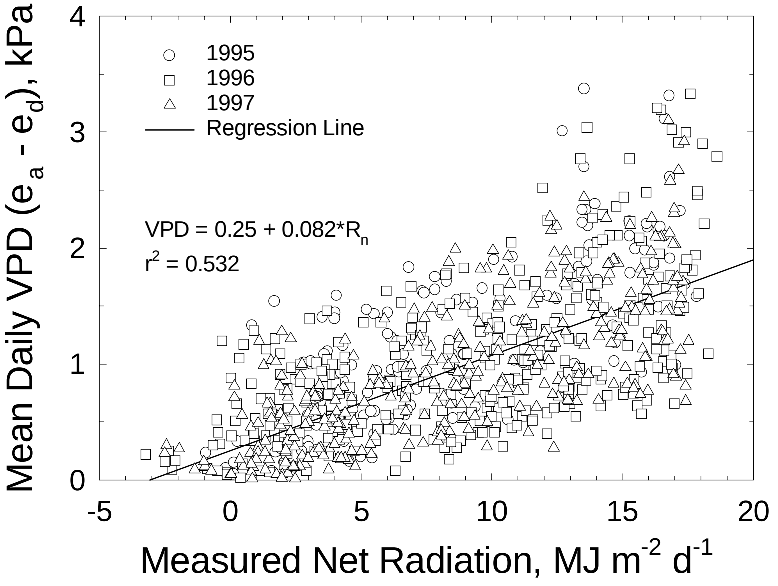

Figure 9. Relationship between mean daily vapor pressure deficit and daily net radiation over irrigated fescue grass at Bushland, TX.