SEASONAL AND MAXIMUM DAILY EVAPOTRANSPIRATION OF IRRIGATED WINTER WHEAT, SORGHUM, AND CORN — SOUTHERN HIGH PLAINS

T. A. Howell, J. L. Steiner, A. D. Schneider, S. R. Evett, J. A. Tolk

ABSTRACT. *Evapotranspiration (ET) is basic information required for irrigation scheduling and for crop growth simulation models. However, many ET models have not been tested for their applicability to the Southern High Plains. In this study, ET was measured for irrigated winter wheat (*Triticum aestivum *L.), sorghum [*Sorghum bicolor *(L.) Moench], and corn (*Zea mays *L.) at Bushland, Texas, in the semi-arid Southern High Plains for various growing seasons from 1988 through 1993. Weighing lysimeters containing Pullman clay loam (*Torrertic Paleustolls*) monoliths were used to measure ET. Weather data from a nearby station were used to compute daily ET values for several widely used reference or potential ET equations. These computed values were then compared by linear regression with the measured ET values for periods of full groundcover (LAI≥3) and with adequate soil water to permit maximum ET. Measured mean seasonal ET was 877 mm for winter wheat, 771 mm for corn, and 578 mm for sorghum. Maximum daily ET rates rarely exceeded 10 mm d^{-1} for the sorghum or corn crops, except for a few days during a brief period of strong advection in 1990 when corn ET rates exceeded 12 mm d^{-1}. Maximum daily ET for wheat exceeded 10 mm d^{-1} on many days during the three seasons due to the high vapor pressure deficits and wind speeds at Bushland during the spring and early summer. The Penman-Monteith equation performed consistently better than other combination and/or radiation/temperature based ET equations in estimating maximum daily ET rates for these crops. The leaf diffusion resistance (r_l) permitting the best agreement between predicted and lysimetrically determined ET was 280 s m^{-1} for sorghum, 252 s m^{-1} for corn, and 135 s m^{-1} for wheat when using the relationship of $r_c = r_l/(0.5\ LAI)$ where LAI is the leaf area index and r_c is canopy resistance in s m^{-1}. These results indicate that the greater seasonal water use by irrigated corn compared with sorghum in this environment was due mainly to the differences in planting date and growing season length since the "apparent" leaf resistances were similar. The even higher seasonal and maximum daily water use of irrigated winter wheat compared with corn and sorghum was due to its longer growing season, its lower leaf resistance, and the high evaporative demand in the spring in the Southern High Plains.*

Keywords. *Aerodynamic resistance, Canopy resistance, Crop-water use, Irrigation, Lysimeters, Reference evapotranspiration, Wind function.*

Winter wheat, corn, and sorghum are principal irrigated crops in the northern Texas High Plains (over 87% of irrigated area), major irrigated crops in the central Texas High Plains (over 54% of irrigated area), but minor irrigated crops (less than 14% of irrigated area) in the southern Texas High Plains where cotton is the major irrigated crop (almost 80% of irrigated area) (Musick et al., 1990). Corn has one of the highest water requirements of irrigated crops in the Southern High Plains (Musick et al., 1990). Sorghum and wheat are produced under full irrigation, limited irrigation, and dryland regimes. Corn, however, is mainly produced under full irrigation regimes (Musick and Dusek, 1980b). Irrigation supplements the 400 to 600 mm annual rainfall. Sprinkler irrigation is expanding in the region (Musick et al., 1988), and the declining well yields result in low irrigation capacities (flow rate per unit land area) (Musick and Walker, 1987). Sprinkler irrigation and low irrigation capacity require precise irrigation management, particularly for corn (Howell et al., 1989), in this region.

The objectives of this article are (1) to report and summarize daily and seasonal ET data for irrigated winter wheat, corn, and sorghum at Bushland, Texas, for several seasons, and (2) to analyze the maximum daily ET values compared with various ET computation methods for the full-cover, well-watered crops. The latter objective is intended to illustrate ET methods that perform well in estimating maximum daily ET in the Southern High Plains environment with routine daily weather station data for use in irrigation scheduling and crop growth models.

LITERATURE REVIEW

Evapotranspiration (ET) measurement methods are described by Hatfield (1990); of these, weighing lysimetry is one of the most accurate methods to determine ET. The

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Bowen ratio and eddy correlation methods are becoming more widely used (Fritschen and Simpson, 1989; Bausch and Bernard, 1992; Dugas et al., 1991). The Bowen ratio method makes several critical assumptions, relies heavily on the precision of net radiation measurement, and has limitations when the ratio is -1.0. Eddy correlation equipment is becoming more robust for seasonal deployment (Kizer et al., 1990) but remains rather fragile for long-term unattended data acquisition. The soil water balance method is commonly used, but it relies heavily on spatially uniform soil water contents for reliable sampling, on precise water input measurements, and on critical information (or assumptions) needed to characterize deep percolation and runoff. Carrijo and Cuenca (1992) indicated neutron probes could be used to determine ET rates over several days to perhaps a week with good accuracy (assuming deep percolation and runoff were minimized).

Jensen et al. (1990) reviewed methods for computing ET and recommended the Penman-Monteith equation (Monteith, 1965) as presented by Allen et al. (1989) as the preferred method for daily reference ET. They proposed that the "standard" alfalfa height be 0.5 m, and that the "standard" grass height be 0.12 m for reference ET models. Burman et al. (1980), Hatfield (1990), Hatfield and Fuchs (1990), Doorenbos and Pruitt (1977), and Jensen (1974) also review ET computation methods. Previously, various methods have defined reference or "potential" ET (Penman, 1948, 1956; Van Bavel, 1966). Recently, reference ET has been more widely accepted as a definition. In practice, reference ET is a hypothetical value depending on weather data and the following specific crop parameters: (1) albedo; (2) emissivity; (3) crop height; and (4) leaf resistance. The first two parameters affect net radiation and energy partitioning into soil heat flux. Crop height affects the aerodynamic characteristics of the crop, which influence sensible and latent heat exchange between the crop canopy and the atmosphere. Leaf resistance affects the reference crop surface resistance to latent heat transfer to the atmosphere. Energy partitioning into soil heat flux (G) is implicitly assumed to be a small component for reference crops, and G is usually estimated by simple relationships based on air temperature or R_n itself.

One goal of ET research has been the identification and evaluation of methods for estimating ET that use readily available data (mainly 24-h weather station data) (Hatfield, 1988; Heermann, 1988; Saxton and Cordery, 1988). The summary by Jensen et al. (1990) is the most complete recent treatment of ET methodology, but earlier reviews by Jensen (1974) and particularly that by Brutsaert (1982) and Doorenbos and Pruitt (1977) provide additional information.

MATERIALS AND METHODS

The study was conducted at the USDA-ARS Laboratory at Bushland, Texas (lat 35°11′N; long 102°06′W; 1170 m elevation above MSL). The ET of the crops was measured with weighing lysimeters (Marek et al., 1988), which have a reported accuracy of 0.05 to 0.02 mm d^{-1} (Howell et al., 1995a), during the 1989-1990, 1991-1992, and 1992-1993 seasons for winter wheat, the 1988 and 1993 seasons for sorghum, and the 1989 and 1990 seasons for corn. The irrigated winter wheat data are described in Howell et al. (1995c), and Tolk et al. (1995) analyzed and discussed the corn data as they related to aerodynamic and energy balance. Two lysimeter fields were planted to each crop in each season. In 1988, 1989, and 1990, both of the sorghum fields (1988) and corn fields (1989 and 1990) were kept well watered. In the other years, one field was always irrigated to meet ET demands and only those data are reported herein. Each lysimeter field is approximately 4.4 ha (210 m E-W × 210 m N-S), and the lysimeter is centered in each field. The predominate wind direction is SW to SSW, and the unobstructed fetch in this direction exceeds 1 km. It is unlikely that local advection affected the measured ET, to an appreciable extent, due to the fetch of the lysimeter fields although the weather station fetch was considerably less.

Table 1 summarizes the agronomic and management details. The wheat was planted flat in all years, but the corn and sorghum were grown on raised beds. All field operations were performed with standard 4.6-m wide row-crop field equipment, except in the immediate 30-m^2 area at each lysimeter where hand-cultural methods were required. Fertility and pest control were applied uniformly to the field area. Irrigations were applied with a 10-span lateral move sprinkler system (Lindsay) with an end-feed hose and aboveground, end guidance cable. The irrigations were scheduled to maintain the soil water profile adequately supplied with water to minimize soil water deficits and to avoid reducing ET and/or yield. The soil water content profile was maintained at about 50% or greater of the extractable soil water.

Plant samples from 1.5-m^2 areas were obtained periodically to measure crop development. These field samples were taken at sites about 10 to 20 m away from the lysimeters in areas of the field representative of the lysimeter vegetation. Crop height, LAI, and aboveground dry matter were measured. Final grain yield was measured by harvesting all the heads or ears in the lysimeter (9 m^2), and dry matter and grain yield at harvest were measured from adjacent plant samples. Wheat and sorghum head samples were threshed with a head thresher in the laboratory, and the ears were hand-shelled. In addition, field yield strips were cut by a combine in both E-W and W-E passes in the center of each irrigation span (10 spans), and the grain was weighed with a field grain cart equipped with a scale. Grain samples were obtained from the combined grain and oven dried to determine the moisture content. All grain yield data are reported at 14% wc (wb) for the wheat and sorghum and 15.5% wc (wb) for the corn.

Solar radiation, wind speed, air temperature, dew point temperature, relative humidity, precipitation, and barometric pressure were measured at an adjacent weather station (Dusek et al., 1987) with an irrigated grass surface (cool season lawn mixture containing bluegrass, perennial rye-grass, etc.). Weather station descriptions and protocols are found in Dusek et al. (1993), Howell et al. (1995c), Steiner et al. (1991), and Tolk et al. (1995). Specific weather instruments used in this study are given below:

Parameter	Instrument
Solar radiation	Eppley PSP
Air temperature/ relative humidity	Variety (See Dusek et al., 1993)
Barometric pressure	YSI 2014
Wind speed	Met-One 014A

Table 1. Agronomic and management information

Parameter	Sorghum 1988	Sorghum 1993	Corn 1989	Corn 1990	Winter Wheat 1989-1990	Winter Wheat 1991-1992	Winter Wheat 1992-1993
Lysimeter field(s)	NW & SW	NE	NE & SE	NE & SE	NW	NE	SW
Row spacing (m)	0.76	0.76	0.76	0.76	0.25	0.25	0.29
Row direction	E-W	E-W	E-W	E-W	E-W	N-S	E-W
Previous crop	Sorghum	Wheat Fallow	Sorghum	Corn	Sorghum Fallow	Corn Fallow	Sorghum Fallow
Cultivar (Agripro)	DK-41Y	DK-56	PIO 3124	PIO 3124	TAM-200	TAM-107	MESA
Planting date	06/20 [172]*	05/27 [147]	04/26 [116]	05/09 [129]	10/10/89 [283]	09/27/91 [270]	09/29/92 [273]
Emergence date	06/27 [179]	06/03 [154]	05/07 [127]	05/18 [138]	10/18/89 [291]	10/07/91 [280]	10/09/92 [283]
Heading date	08/16 [229]	07/27 [208]	07/22 [203]	07/26 [207]	05/09/90 [129]	04/27/92 [118]	05/05/93 [125]
Anthesis date	08/22 [235]	08/05 [217]	08/01 [213]	08/03 [215]	05/16/90 [136]	05/08/92 [129]	05/13/93 [133]
Phys. mat. date	10/01 [275]	09/30 [273]	10/10 [283]	09/21 [264]	06/14/90 [165]	06/19/92 [171]	06/21/93 [172]
Harvest date	11/14 [319]	10/05 [278]	10/24 [298]	10/29 [302]	06/26/90 [177]	07/06/92 [188]	06/28/93 [179]
Plant dens. (# m^{-2})	16	20	6	6	190	193	131
Fert. [g(N) m^{-2}]	12	11	16	25	13	11	8
Lys. yield† (kg m^{-2})	0.786 NW 0.903 SW	0.898 NE	1.237 NE 1.194 SE	1.148 NE 1.327 SE	0.535 NW	0.379‡ NE	0.600 SE
Lys. dry matter (kg m^{-2})	1.439 NW 1.652 SW	2.006 NE	2.168 NE 2.175 SE	2.127 NE 2.177 SE	na§	1.588 NE	na§
Combine yield (kg m^{-2})	0.726 NW 0.782 SW	1.009 NE	1.005 NE 0.947 SE	1.051 NE 1.142 SE	0.520 NW	0.680 NE	0.538 SE
Field d. matter (kg m^{-2})	1.687 NW 1.612 SW	2.002 NE	1.984 NE 2.212 SE	2.280 NE 2.560 SE	1.316 NW	2.113 NE	1.848 SE
Field yield (kg m^{-2})	0.940 NW 0.894 SW	1.144 NE	1.132 NE 1.212 SE	1.289 NE 1.337 SE	0.490 NW	0.778 NE	0.747 SE
ET (mm)	535 NW 562 SW	637 NE	779 NE 701 SE	772 NE 831 SE	791 NW	909 NE	931 SW

* Numbers in brackets are day of year.

† Grain yields are reported at 14% wc (wb) for sorghum and wheat and 15.5% wc (wb) for corn.

‡ Plants were lodged.

§ Dry matter was not harvested to leave residue for subsequent fallow research.

All transducers were measured at 0.167 Hz (6 s) frequency by a Campbell Scientific CR-7X data logger, signals were averaged for 15 min, and two 15-min means were composited into a 30-min mean. Daily (24 h) averages, maximum, or minimum values were determined from the 0.167 Hz samples. Data were transferred daily via telephone modem from the CR-7X to a laboratory personal computer.

Lysimeter mass was determined using a Campbell Scientific CR-7X data logger to measure and record the lysimeter load cell (Alphatron S50) signal at 0.5 Hz (2 s) frequency. The load cell signal was averaged for 15 min and composited to a 30-min mean, and the lysimeter mass resolution was 0.01 mm and its accuracy exceeded 0.05 mm (Howell et al., 1995a). Daily ET was determined as the difference between lysimeter mass losses (from evaporation and transpiration) and lysimeter mass gains (from irrigation, precipitation, or dew) divided by the lysimeter area (9 m^2). Vacuum drainage was provided by a pump regulated to 10 kPa, and the drainage effluent was held in two tanks suspended from the lysimeter (their mass was part of the total lysimeter mass) and independently weighed by load cells (drainage rate data are not reported here). ET for each 24-h period was multiplied by 1.02 to adjust the lysimeter area to the mid point between the two walls (10 mm air gap; 9.5 mm wall thickness; 9.18 m^2 area instead of 9.00 m^2 area). This correction would be applicable for full-cover crops, but it would not be necessary for bare soil conditions with no plant overhang. Nevertheless, it was applied to all data uniformly.

Daily ET data were screened for this analysis to represent full groundcover (defined by the leaf area index exceeding 3.0 m^2 m^{-2}), ample soil water to avoid restricted crop water uptake, and days without irrigations, drainage, or rain events that might cause any mass errors in the lysimeter measurements. These ET data were combined with the weather station data on those days and with the crop height and LAI data.

Daily ET based on the Penman-Monteith equation for each crop was computed as:

$$ET_{pm} = \frac{\Delta(R_n + G)/\lambda + (8.64\times 10^4)(\rho C_p/\lambda)(e_a - e_d)/r_a}{[\Delta + \gamma(1 + r_c/r_a)]} \quad (1)$$

where ET_{pm} is the estimated crop ET in mm d^{-1}, Δ is the slope of the saturated vapor pressure curve ($\partial e_s/\partial T$) in kPa °C^{-1}, R_n is net radiation in MJ m^{-2} d^{-1}, G is soil heat flux in MJ m^{-2} d^{-1} (positive when heat flux is toward the surface), λ is latent heat of vaporization in MJ kg^{-1}, ρ is air density in kg m^{-3}, C_p is specific heat of moist air in MJ kg^{-1} °C^{-1} [1013 J kg^{-1} °C^{-1}], e_a is mean saturated vapor pressure in kPa at T_{max} and T_{min} {$e_a = [e_s(T_{max}) + e_s(T_{min})]/2$ where $e_s(T)$ is saturated vapor pressure in kPa at temperature T}, e_d is saturated vapor pressure in kPa at mean daily dew point temperature (T_{dew}), γ is the psychrometric constant in kPa °C^{-1} [C_p P_b)/(0.622 λ)], r_a is aerodynamic resistance in s m^{-1}, r_c is canopy surface resistance in s m^{-1}, and P_b is barometric pressure in kPa.

In equation 1, the parameters were calculated using the ASCE Manual No. 70 equations (Jensen et al., 1990) based on Allen (1986), Wright (1982, 1988), and Allen et al. (1989). R_n was measured at each lysimeter with miniature net radiometers (Micromet, Inc. before 1989 and REBS, Inc. thereafter). G was measured at 100-mm depth before 1989 (Micromet, Inc., soil heat flux plates) and at 50-mm depth after 1989 (REBS soil heat flux plates). Soil heat flux was corrected for thermal storage in the soil layer above the plates as:

$$G = G_z + [2.4\, z\, (T_0 - T_{24})] \qquad (2)$$

where G is soil heat flux (positive toward the surface) at the soil surface in MJ m^{-2} d^{-1}, G_z is the measured soil heat flux in MJ m^{-2} d^{-1} at depth z in m, and T_0 and T_{24} are the mean soil temperatures in °C in the layer above the heat flux plates (0 to z) at the beginning of the day and the end of the day, respectively. The parameter 2.4 MJ m^{-3} °C^{-1} is the soil specific heat computed for the Pullman soil based on its constituents (minerals, organic matter, etc.) for a soil water content of 0.25 m^3 m^{-3}, which we assumed to be constant for these well-watered days with frequent sprinkler irrigations.

The aerodynamic resistance was estimated following Allen et al. (1989) and Steiner et al. (1991) by adjusting 2-m wind speeds over grass (U_{2g}) to 2-m wind speeds above the crop. The canopy surface resistance was estimated as:

$$r_c = \frac{r_l}{(0.5\ \mathrm{LAI})} \qquad (3)$$

where r_l is the leaf resistance in s m^{-1} and LAI is leaf area index in m^2 m^{-2} following Allen et al. (1989). The leaf resistance, r_l, was varied from 100 s m^{-1} to 250 s m^{-1}. Allen (1986), Allen et al. (1989), and Jensen et al. (1990) recommended r_l as 100 s m^{-1} for grass and alfalfa, but Steiner et al. (1991) reported a r_l of 163 s m^{-1} fit lysimeter measured daily water use rates for full groundcover sorghum at Bushland. We did not attempt to optimize r_l to fit our data, but we did determine the r_l magnitude that equated the mean Penman-Monteith ET to the measured ET_l. In addition, r_c was estimated using the well-watered baseline method from Idso (1983) as adapted and tested by Steiner et al. (1991) as follows:

$$r_c = \left\{\frac{[1 - b(\Delta + \gamma)]}{1 - b\Delta}\right\}\left[\frac{a\,\rho\, C_p}{b\,\gamma\, R_{nf}}\right] \qquad (4)$$

where R_{nf} is the net radiation flux in W m^{-2} and a and b are empirical constants defined by the well-watered baseline given as:

$$T_c - T_a = a - b\ \mathrm{VPD} \qquad (5)$$

where T_c is crop canopy temperature in °C, T_a is air temperature in °C, and VPD is ambient vapor pressure deficit in kPa. Values for "a" and "b" are given in table 2. The ET for this Penman-Monteith-Idso equation was called ET_{pmi}.

Three forms of the combination equation (Penman, 1948) were also used to compute "reference" or potential ET as follows:

Table 2. Parameters used to compute ET_{pmi} based on well-watered baselines

Crop	Reference	a (°C)	b (°C kPa^{-1})
Winter wheat	Howell et al. (1986)	1.08	2.09
Sorghum	O'Toole and Hatfield (1983)	2.53	1.96
Corn	Idso (1982)	3.11	1.97

$$ET_{p48} = \frac{\Delta(R_n + G)/\lambda + \gamma(e_o - e_d)(6.43 + 3.453 U_{2g})/\lambda}{(\Delta + \gamma)} \qquad (6)$$

$$ET_{fao} = \frac{\Delta(R_n + G)/\lambda + \gamma(e_o - e_d)(6.43 + 5.556 U_{2g})/\lambda}{(\Delta + \gamma)} \qquad (7)$$

$$ET_{kim} = \frac{\Delta(R_n + G)/\lambda + \gamma(e_a - e_d)(4.82 + 6.385 U_{2g})/\lambda}{(\Delta + \gamma)} \qquad (8)$$

where R_n and G were measured and described earlier and ET_{p48}, ET_{fao}, and ET_{kim} represent the wind functions derived by Penman (1948) for grass, by Doorenbos and Pruitt (1977) for grass, and by Wright and Jensen (1972) for alfalfa, respectively. Vapor pressure deficit (VPD) was computed similarly to that shown in the ET_{pm} equation (eq. 1) for ET_{kim} (VPD = $e_a - e_d$), but the ET_{p48} and ET_{fao} equations (eqs. 6 and 7) used e_o computed at mean air temperature [$T = T_{min} + T_{max})/2$; $e_o = e_s(T)$] to compute the VPD (VPD = $e_o - e_d$). Both VPD calculation methods perform well at Bushland (Howell and Dusek, 1995; Steiner et al., 1991). Priestley and Taylor (1972) potential ET was computed as:

$$ET_{pt} = \frac{1.26\ \Delta(R_n + G)/\lambda}{(\Delta + \gamma)}\ . \qquad (9)$$

The radiation-temperature-based ET equation developed by Jensen and Haise (1963) and modified as described later in Jensen et al. (1990) was computed as:

$$ET_{jh} = C_t\,(T - T_x)\,R_s\,/\,\lambda \qquad (10)$$

where C_t and T_x are coefficients taken as 0.0234 °C^{-1} and −8.76 °C, respectively, following Steiner et al. (1991) for Bushland conditions. These equations were coded in a spreadsheet program, and components were verified with REF-ET, version 2.1 (Allen, 1990). Linear regressions were computed among ET estimates for all these models (eq. 1 and eqs. 6 through 10) and ET_l as measured by the lysimeters.

Empirical wind functions were fit for each crop using equation 8 as follows:

$$f(U_2) = \frac{ET_l(\Delta + \gamma) - \Delta(R_n + G)/\lambda}{\lambda(e_a - e_d)} \qquad (11)$$

where $f(U_2)$ is in mm d^{-1} kPa^{-1}. Residual canopy resistance (r_c) was computed using equation 1 and the estimated canopy aerodynamic resistance (r_a).

Maximum crop ET was compared with the above reference ET equations directly. In practice, these two would most likely be characterized using an empirical crop coefficient approach. However, in theory the PM equation (and the other combination equations in concept) could be applied to any crop, water, or soil surface that matched the conditions defining r_a and r_c. Several crop growth models use the PM equation to compute the "maximum" non-stressed water use rate and then use "stress" factors to reduce ET and crop growth. The information used to characterized r_c might be improved in these models if crop specific factors could be used (i.e., a r_c value specified for corn for a corn growth model).

RESULTS AND DISCUSSION

The data screening for days with well-watered conditions without irrigation or rain and when LAI>3.0 resulted in 84 days for the wheat seasons, 148 days for the corn seasons, and 112 days for the sorghum seasons. Table 3 provides a summary of the 24-h climatic parameters and crop characteristics for these screened data. The winter wheat data cover a temperature range from 2.4 to 31.4°C. All the data sets included mean 2-m wind speeds exceeding 6 m s^{-1}. The lowest 2-m wind speeds (daily mean) ranged from 1.2 to 2.1 m s^{-1}, which might exceed the long-term daily mean wind speeds at many locations. Of note, is the typically low mean value of G indicating the effects of the full crop canopies on absorbing the radiant energy. R_n (net radiation) averaged 59% of R_s (solar radiation) for the sorghum, 61% for the corn, but was lower at 53% for the winter wheat. The exact reason why R_n/R_s was lower for wheat has not been fully explored, but we suspect albedo and sun angle differences.

Table 3. Summary of the 24-h climatic variables used to evaluate evapotranspiration models for irrigated crops with full groundcover and amply supplied with water and crop characteristics during these periods at Bushland, Texas

Parameter	Mean	Maximum	Minimum	No.
Winter Wheat 1989-1990, 1991-1992, 1992-1993 Seasons				
Tmean (°C)	14.1	21.6	2.4	84
Tmax (°C)	22.4	31.4	8.7	84
Tmin (°C)	5.6	14.4	–2.8	84
Tdew (°C)	1.1	8.2	–6.8	84
VPD (kPa)	1.20	2.24	0.42	84
2-m wind speed (m s^{-1})	4.6	7.4	1.9	84
Solar rad. (MJ m^{-2} d^{-1})	23.4	29.8	11.5	84
Net rad. (MJ m^{-2} d^{-1})	13.5	20.1	7.4	84
Soil heat flux (MJ m^{-2} d^{-1})	–0.01	1.28	–1.49	84
Crop height (m)	0.58	1.10	0.15	84
Leaf area index (m^2 m^{-2})	4.67	7.20	2.95	84
Corn 1989 and 1990 Seasons				
Tmean (°C)	22.7	27.1	12.3	148
Tmax (°C)	29.6	36.4	20.6	148
Tmin (°C)	15.7	19.8	3.8	148
Tdew (°C)	12.3	17.2	3.6	148
VPD (kPa)	1.56	2.94	0.46	148
2-m wind speed (m s^{-1})	3.5	6.6	1.2	148
Solar rad. (MJ m^{-2} d^{-1})	23.1	29.1	11.9	148
Net rad. (MJ m^{-2} d^{-1})	14.1	18.6	5.9	148
Soil heat flux (MJ m^{-2} d^{-1})	–0.03	1.03	–0.71	148
Crop height (m)	2.40	2.87	0.92	148
Leaf area index (m^2 m^{-2})	4.40	5.78	2.75	148
Sorghum 1988 and 1993 Seasons				
Tmean (°C)	21.2	27.6	13.2	112
Tmax (°C)	28.7	35.9	19.6	112
Tmin (°C)	13.8	20.7	3.8	112
Tdew (°C)	10.6	16.8	0.0	112
VPD (kPa)	1.52	2.59	0.41	112
2-m wind speed (m s^{-1})	4.1	6.1	2.1	112
Solar rad. (MJ m^{-2} d^{-1})	22.2	28.5	13.3	112
Net rad. (MJ m^{-2} d^{-1})	13.1	19.8	7.0	112
Soil heat flux (MJ m^{-2} d^{-1})	0.10	1.45	–0.85	112
Crop height (m)	1.10	1.48	0.68	112
Leaf area index (m^2 m^{-2})	3.82	5.17	2.90	112

WINTER WHEAT

Crop development is shown in figure 1 for the three wheat seasons. The wheat cultivar was changed in each season (table 1) for various reasons. TAM-200 (used in 1989-1990) is somewhat susceptible to winter kill, and it was important to avoid any potential problems (although there were no problems in 1989-1990). TAM-107 (used in 1991-1992) grew excessively tall and lodged under the conditions of 1991-1992 for the high management inputs (fertility and water). Other plots at Bushland with TAM-107 also lodged badly that year. Mesa (used in 1992-1993) is a somewhat shorter cultivar but sacrifices some yield potential. The maximum LAI in 1989-1990 and 1992-1993 barely reached or exceeded 4.0; however, dry matter exceeded 1.6 kg m^{-2} in each year indicative of good wheat crops (Musick and Porter, 1990). The LAI was the highest in 1991-1992, and the dry matter exceeded 2.0 kg m^{-2} with a combine harvested yield of 680 g m^{-2}. The lysimeter grain yield in that year was only 379 g m^{-2}, due to the lodged crop. However, grain yields in 1989-1990 and 1992-1993 were typical of irrigated plot yields (535 and

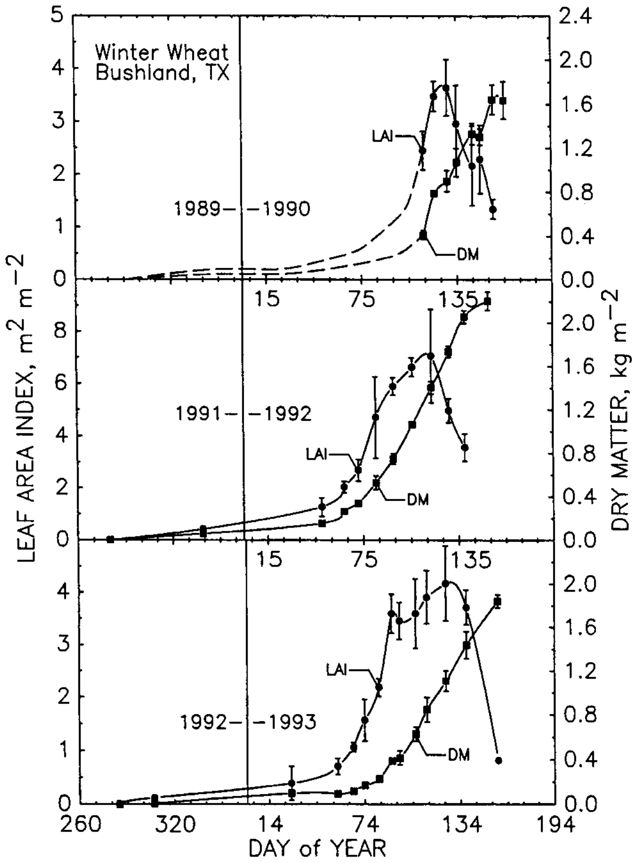

Figure 1–Leaf area index (LAI) and dry matter (DM) development for irrigated winter wheat at Bushland, Texas, for the 1989-1990, 1991-1992, and 1992-1993 growing seasons. The error bars are ± one standard deviation from the mean.

600 g m^{-2}, respectively). Temperatures during grain filling can dramatically affect grain-fill duration in this environment (Wiegand and Cuellar, 1981; Howell et al., 1995c). Grain-fill periods were substantially shorter in 1989-1990 and 1992-1993 compared with the longer grain-fill period in 1991-1992, a cooler season.

Daily ET for winter wheat is shown in figure 2 for each season. Fall ET rates were variable depending on fall conditions (planting date, temperatures, etc.). Winter ET rates in the 1989-1990 season were low due to the late planting, dry fall conditions, and limited crop development going into winter. Winter-time ET rates seldom exceeded 1 or 2 mm d^{-1}, but these ET rates can accumulate to substantial ET values over the nearly two-month winter (Dec. and Jan.). By mid to late February (DOYs 46-59), ET rates (fig. 2) and crop growth (fig. 1) began to accelerate. ET rates are generally maximum following heading. In all years, maximum daily ET rates exceeded 12 mm d^{-1} on several occasions. The high ET rates exceeding 14 mm d^{-1} in 1991-1992 just after heading (and before any lodging) are discussed in Howell et al. (1995c) and were mainly caused by high vapor pressure deficits and high wind speeds (Skidmore et al., 1969). Peak ET rates for wheat are comparable to the maximum measured values of 14.2 mm d^{-1} for alfalfa in Nebraska (Rosenberg and Verma, 1978) and exceeded the maximum values of 11.0 mm d^{-1} for alfalfa in Idaho (Wright, 1988). Generally, ET rates declined dramatically with senescence after physiological maturity until harvest. But the exact physiological maturity date is difficult to determine for wheat because it does not form a black-layer like corn or sorghum.

Seasonal ET values (table 1) were 791, 909, and 939 mm in the 1989-1990, 1991-1992, and 1992-1993 seasons, respectively. These values are greater than those summarized based on soil water balance by Musick and Porter (1990) for Bushland (mean was 710 mm) found by Jensen and Sletten (1965a), Schneider et al. (1969), Musick and Dusek (1980a), Eck (1988) and all using surface irrigation. Schneider and Howell (1997) reported mean seasonal wheat ET based on soil water balance for full irrigation of 596 to 783 mm in 1994 and 1995 using various sprinkler methods, but maximum yields were in the 437 to 528 g m^{-2} range. The reasons the lysimetrically determined ET rates appear to be higher than previous measurements at Bushland were most likely the growing season environments and/or the more frequent sprinkler irrigations.

Table 4 summarizes the comparisons between ET methods for estimating maximum ET of winter wheat. A r_l value of 135 s m^{-1} provided a mean ET_{pm} similar to that measured by the lysimeters. The ET_{pmi} performed well ($r^2 = 0.968$) without any fitting (except for any fitting inherent with the base lines that were also determined at Bushland) and overestimated mean measured maximum daily ET by 3%. The mean r_c value for the ET_{pmi} for wheat was 55 s m^{-1}, and the mean computed "residual" r_c value was 56 s m^{-1}. The Penman equation (ET_{p48}) underpredicted mean daily maximum ET (by 9%) while the other combination equations overpredicted mean daily maximum ET of wheat by 8-27%. The radiation-temperature based equations (ET_{jh} and ET_{pt}) underpredicted mean daily maximum wheat ET by 30 to 37%. Jamieson (1982) reported that the Priestley-Taylor equation slightly (9%) underpredicted maximum ET for barley. Meyer et al. (1987) found that a combination equation with a locally derived wind function underestimated maximum ET of wheat but also found nighttime ET strongly related to wind speed. All ET equations, except the Penman-Monteith-based equations, had significant intercepts (biases). Figure 3 shows that the fitted Penman-Monteith ET equation for a r_l of 135 s m^{-1} for full-cover wheat agreed well with the lysimeter measured ET. The $S_{y/x}$ was 1.05 mm d^{-1} for the regression with an r^2 of 0.982, and the lysimeter ET range was from less than 3 mm d^{-1} to greater than 13 mm d^{-1}.

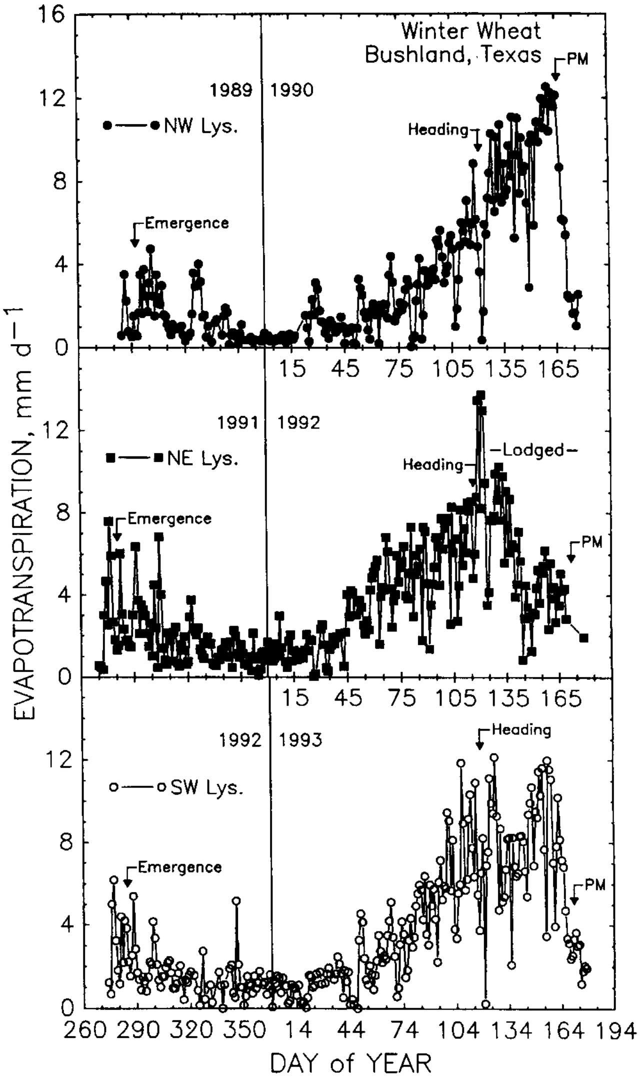

Figure 2–Daily evapotranspiration of irrigated winter wheat at Bushland, Texas, for the 1989-1990, 1991-1992, and 1992-1993 growing seasons from planting to harvest. The PM symbol refers to physiological maturity.

SORGHUM

Figure 4 shows the crop development in the 1988 and 1993 seasons. In 1988, the hybrid was a medium maturity hybrid which is grown under both irrigation and dryland in this region. It produced a maximum LAI slightly exceeding 4.0 and a dry matter exceeding 1.4 kg m^{-2}. The grain yield averaged 845 g m^{-2} (table 1) for the two lysimeters in that year and was about 12% greater than the field combined

Table 4. Mean, maximum, and minimum daily evapotranspiration of well-watered, full-ground-cover crops (ET_l) or as estimated ET_p by several equations at Bushland, Texas. Regression coefficients are for estimated ET_p (dependent variable) versus ET_l (independent variable) for each equation

		Evapotranspiration (mm d^{-1})					Regression Coefficients			
Model	Equations	Mean	Maximum	Minimum	SE of Mean	ET_p/ET_l Ratio	Intercept (mm d^{-1})	Slope	r^2	$S_{y/x}$ (mm d^{-1})
			Winter Wheat 1989-1990, 1991-1992, and 1992-1993 Seasons							
ET_l	—	7.39	13.86	2.61	0.25	—	—	—	—	—
$ET_{pm(100)}$*	1, 3	8.37	16.52	3.53	0.32	1.13	ns	1.14	0.984	1.12
$ET_{pm(150)}$	1, 3	7.11	14.48	3.34	0.27	0.96	ns	0.96	0.981	1.04
$ET_{pm(135)}$	1, 3	7.42	15.03	3.13	0.28	1.01	ns	1.01	0.982	1.05
ET_{pmi}	1, 4	7.68	16.40	2.43	0.33	1.03	ns	1.06	0.968	1.48
ET_{pen48}	6	6.53	10.61	3.31	0.17	0.91	1.98	0.62	0.770	0.77
ET_{fao}	7	7.83	13.29	3.97	0.23	1.08	1.92	0.80	0.782	0.96
ET_{kpen}	8	9.23	16.32	4.30	0.29	1.27	1.66	1.02	0.785	1.22
ET_{jh}	10	5.11	8.41	1.92	0.16	0.70	1.30	0.52	0.616	0.93
ET_{pt}	9	4.44	7.04	2.35	0.12	0.63	2.16	0.31	0.401	0.86
			Corn 1989 and 1990 Seasons							
ET_l	—	6.72	12.43	2.50	0.15	—	—	—	—	—
$ET_{pm(200)}$	1, 3	7.60	12.21	3.02	0.17	1.14	1.04	0.98	0.734	1.05
$ET_{pm(250)}$	1, 3	6.74	10.79	2.68	0.15	1.01	0.90	0.87	0.734	0.94
$ET_{pm(252)}$	1, 3	6.71	10.74	2.67	0.15	1.01	0.89	0.87	0.734	0.86
ET_{pmi}	1, 4	5.67	10.17	1.59	0.15	0.84	ns	0.85	0.980	0.85
ET_{pen48}	6	6.87	11.53	3.62	0.12	1.05	1.89	0.74	0.793	0.68
ET_{fao}	7	7.90	14.17	3.93	0.16	1.20	1.71	0.92	0.748	0.95
ET_{kpen}	8	8.72	15.97	4.07	0.18	1.32	1.60	1.06	0.715	1.19
ET_{jh}	10	6.90	9.82	3.48	0.12	1.05	2.19	0.71	0.764	0.71
ET_{pt}	9	5.38	7.51	2.35	0.09	0.83	2.31	0.46	0.619	0.64
			Sorghum 1988 and 1993 Seasons							
ET_l	—	5.58	10.20	2.37	0.17	—	—	—	—	—
$ET_{pm(200)}$*	1, 3	6.73	11.51	2.22	0.20	1.21	ns	1.20	0.986	0.85
$ET_{pm(250)}$	1, 3	5.96	10.31	1.94	0.18	1.07	ns	1.06	0.987	0.72
$ET_{pm(280)}$	1, 3	5.58	9.70	1.80	0.17	1.00	ns	1.00	0.988	0.66
ET_{pmi}	1, 4	4.90	9.36	1.16	0.17	0.87	ns	0.88	0.983	0.69
ET_{pen48}	6	6.75	10.66	3.11	0.15	1.25	2.19	0.82	0.835	0.64
ET_{fao}	7	7.93	12.86	3.44	0.18	1.47	2.54	0.97	0.771	0.93
ET_{kpen}	8	9.01	14.79	3.84	0.22	1.67	3.00	1.08	0.688	1.28
ET_{jh}	10	6.44	9.97	2.99	0.16	1.19	1.65	0.86	0.811	0.73
ET_{pt}	9	4.95	7.68	2.43	0.12	0.92	1.55	0.61	0.699	0.71

* Subscripts for the ET_{pm} models refer to the r_l value in s m^{-1}.

yield. In 1993, the earlier planting and longer maturity hybrid (table 1) increased the maximum LAI to over 5.0 and dry matter to over 2.0 kg m^{-2} and grain yield to 898 g m^{-2}. These yields are typical of the mean irrigated sorghum performance tests summarized for the Texas High Plains for 1981-1985 of 803 g m^{-2} (Krieg and Lascano, 1990).

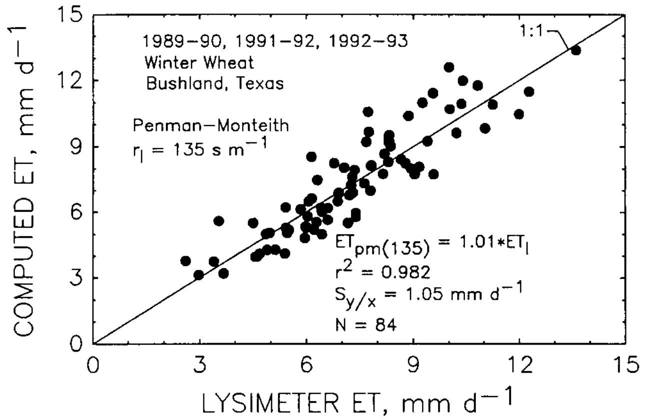

Figure 3–Maximum daily evapotranspiration (ET) of irrigated winter wheat at Bushland, TX, for the 1989-90, 1991-92, and 1992-93 growing seasons for days with full-ground cover compared with computed ET by the Penman-Monteith equation with r_l = 135 s m^{-1}.

Daily ET rates are shown in figure 5 for the two sorghum seasons. ET rates approached maximum values at the early boot stage (5-10 days before heading) when LAI was maximum. One day (DOY 219) had an ET rate exceeding 11 mm d^{-1} in 1988, and none exceeded 10 mm d^{-1} in the 1993 season. The ET rates declined following heading. Because sorghum is a perennial species and does not senesce or go dormant (until killed by frost in this environment), ET rates remained relatively high after physiological maturity and even past harvest. Unless sorghum is terminated by herbicides, tillage, or frost, ET continues because the plant maintains green leaves. In both seasons, ET rates were still about 4 mm d^{-1} at physiological maturity.

Seasonal ET (table 1) averaged 549 mm in 1988 and 637 mm in 1993 when the earlier planting and longer maturity hybrid were studied. Jensen and Sletten (1965b) reported a mean ET of irrigated sorghum of 559 mm at Bushland; Stewart et al. (1983) reported a mean ET for fully irrigated sorghum of 619 mm at Bushland; Musick et al. (1963) reported a range of maximum ET for sorghum from studies at Garden City, Kansas, of 584 to 635 mm; and Chaudhuri and Kanemasu (1985) reported a range of ET from 549 to 584 mm for different hybrids at

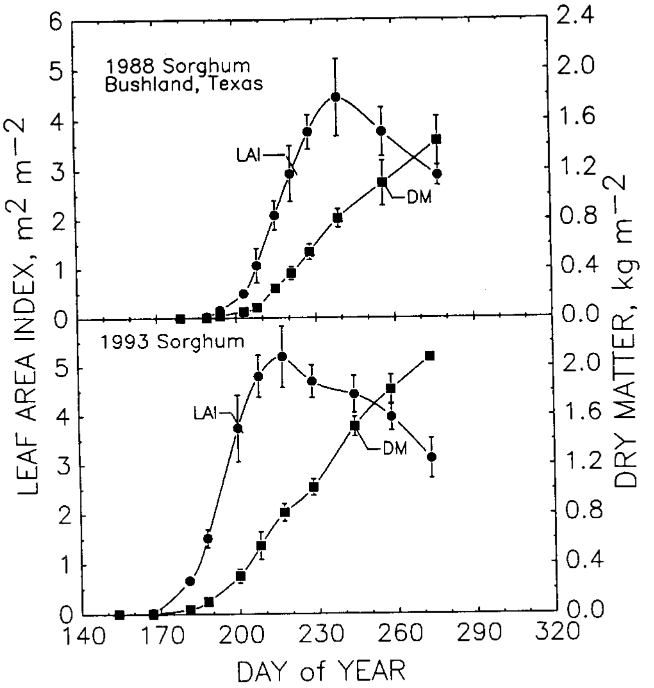

Figure 4–Leaf area index (LAI) and dry matter (DM) development for irrigated sorghum at Bushland, Texas, for the 1988 and 1993 growing seasons. The error bars are ± one standard deviation from the mean.

Manhattan, Kansas; all using surface irrigation methods. Schneider and Howell (1995) reported mean fully irrigated sorghum ET ranging from 550 to 618 mm using LEPA and overhead spray. The seasonal ET values at Bushland reflect these ranges and clearly show that sorghum has a much lower ET under full irrigation than wheat or corn (see next discussion on corn).

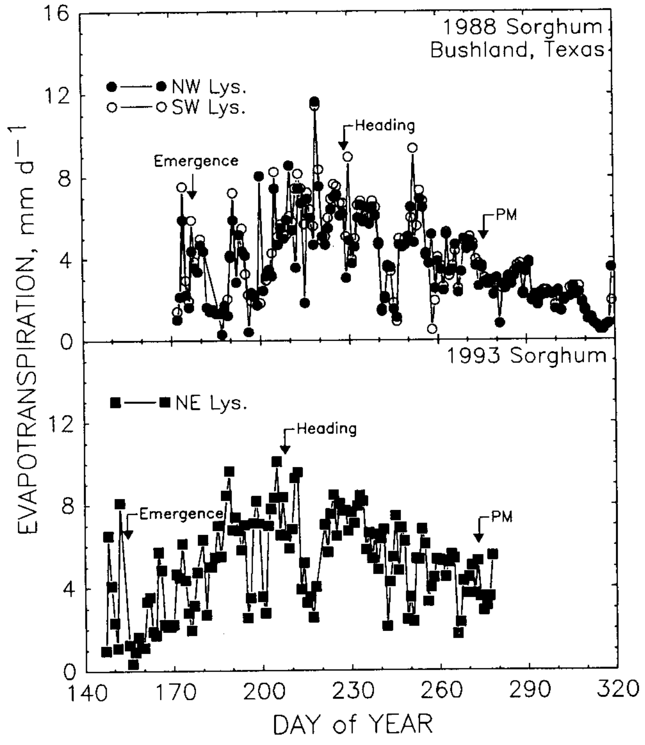

Figure 5–Daily evapotranspiration of irrigated sorghum at Bushland, Texas, for the 1988 and 1993 growing seasons from planting to harvest. The PM symbol refers to physiological maturity.

Table 4 summarizes the comparisons between ET methods for sorghum with full groundcover. A r_l value of 280 s m^{-1} provided a mean ET_{pm} similar to that measured by the lysimeters. The ET_{pmi} performed well ($r^2 = 0.983$) (without any fitting using sorghum baseline parameters from California), but not as well as reported for the 1987 and 1988 sorghum data analyzed by Steiner et al. (1991). The ET_{pmi} did underpredict the mean maximum daily ET of sorghum by 13%. The ET_{pmi} did have a negligible bias (intercept) and a relatively low $S_{y/x}$. The mean r_c value for the ET_{pmi} for sorghum was 137 s m^{-1}, and the mean computed "residual" r_c was 105 s m^{-1}. Like Steiner et al. (1991) reported, all the combination equations over-predicted maximum ET rates for sorghum (by 25-67%), and they had significant and large biases (intercepts). The Priestley-Taylor equation did well in representing the mean daily maximum measured ET, but it had a large bias (intercept) and a low slope. Figure 6 shows the maximum daily ET values for sorghum for the fitted Penman-Monteith equation using a r_l of 280 s m^{-1} for full-cover conditions compared with the measured lysimeter values. The $S_{y/x}$ was 0.66 mm d^{-1} for the regression with a r^2 of 0.988, and the lysimeter measured ET range was from less than 3 mm d^{-1} to slightly greater than 10 mm d^{-1}.

CORN

Figure 7 shows the crop development during the two years (1989 and 1990). The crops grew slightly differently in each year on these two fields. In 1989, the north field was a little taller and more vigorous, while in 1990 the south field was a little taller and more vigorous, but the differences were relatively small. The LAI and dry matter were plotted separately for the two fields in 1990 to show this difference and variability. Maximum LAI exceeded 5.0 in both years, and in 1990 the southeast field LAI approached 6.0. LAI declined after tasseling each year and dramatically declined at about mid-grain fill with senescence. Maximum dry matter was 2.2 kg m^{-2} in 1989, and it exceeded 2.4 kg m^{-2} in 1990. Mean lysimeter grain yield was 1.22 kg m^{-2} in 1989 and 1.24 kg m^{-2} in 1990, and mean combined yields were 0.98 and 1.10 kg m^{-2}, respectively. This is somewhat

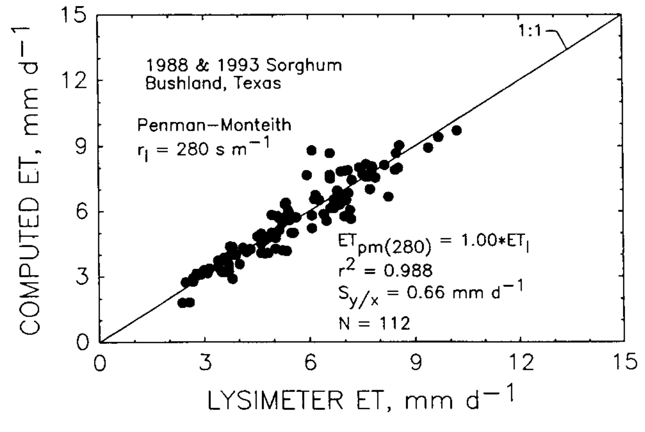

Figure 6–Maximum daily evapotranspiration (ET) of irrigated sorghum at Bushland, Texas, for the 1988 and 1993 growing seasons for days with full groundcover compared with computed ET by the Penman-Monteith equation with r_l = 280 s m^{-1}.

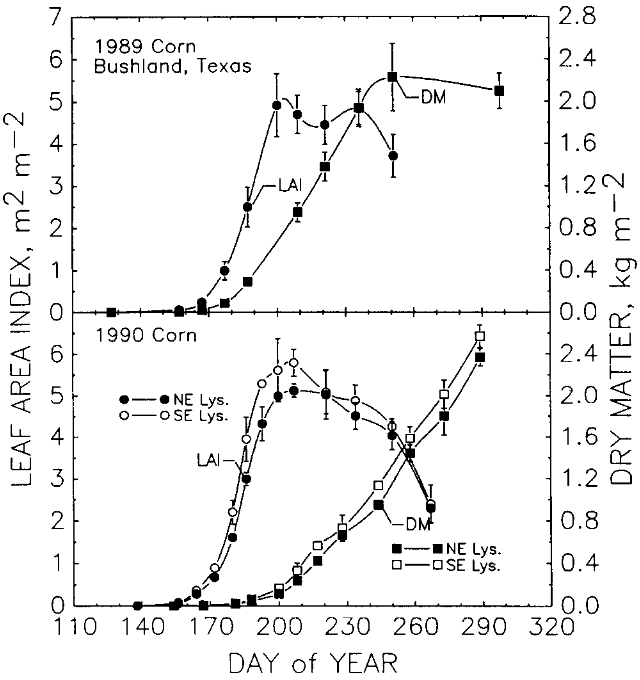

Figure 7–Leaf area index (LAI) and dry matter (DM) development for irrigated corn at Bushland, Texas, for the 1989 and 1990 growing seasons. The error bars are ± one standard deviation from the mean.

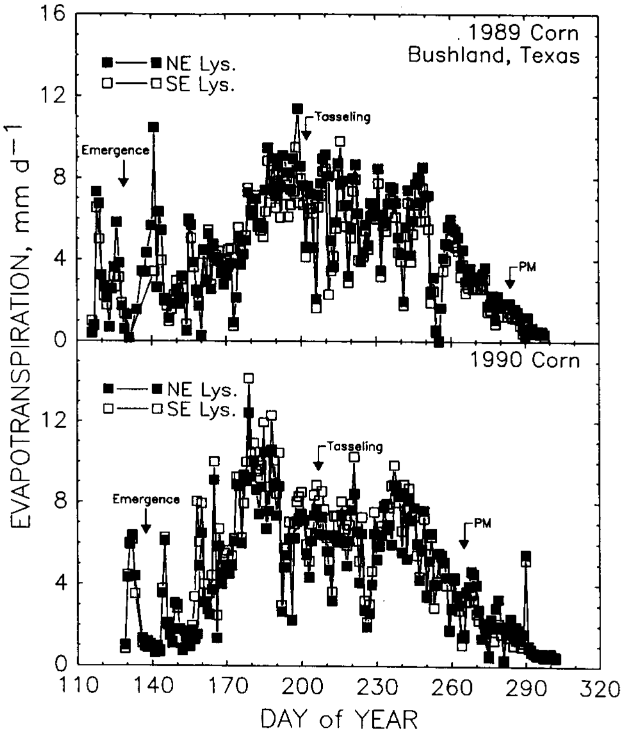

Figure 8–Daily evapotranspiration (ET) of irrigated corn at Bushland, Texas, for the 1989 and 1990 growing seasons from planting to harvest. The PM symbol refers to physiological maturity.

less than the range suggested by Rhoades and Bennett (1990) of 1.10 to 1.50 kg m^{-2} to be expected for irrigated corn. But our yields are similar to the yield range reported by Musick and Dusek (1980b), Eck (1984), and Howell et al. (1989) for fully irrigated corn at Bushland.

Daily ET rates for irrigated corn are shown in figure 8 for both seasons. The maximum ET rate in 1989 occurred a few days before tasseling at maximum LAI (fig. 7). In 1990, however, an extended period of meso-scale advection increased the ET rates to 10 to 14 mm d^{-1} prior to tasseling (LAIs were above 3.0). About midway through the grain-fill period in each year (at about the dent stage), ET rates began to decline in response to the declining green LAI and developing crop senescence as physiological maturity approached. One day (DOY 199) had an ET rate in excess of 11 mm d^{-1} in 1989, but several days had those magnitude rates in 1990 during the period of meso-scale advection. Interestingly, both corn and sorghum have considerably lower maximum ET rates during mid summer at Bushland than winter wheat did in the late spring and early summer. This is due to the climatic pattern of low dew point temperatures and high wind speeds in the spring, while the summer has lower wind speeds and lower vapor pressure deficits even though air temperatures may be higher. In addition, clear sky conditions may occur more often in the spring before afternoon convective cloud patterns establish that are more common in the late spring and summer.

Seasonal ET values (table 1) averaged 740 and 802 mm for 1989 and 1990, respectively. Fully irrigated corn water use at Bushland, which was based on soil water balance and did not account for any percolation, has been reported to vary from 670 to 790 mm by Musick and Dusek (1980b), from 783 to 1003 mm by Eck (1984) for surface irrigation, 838 mm by Howell et al. (1989) for sprinkler irrigated corn, and 786 to 973 mm by Howell et al. (1995b) for LEPA irrigated corn. Again, the lysimetrically measured seasonal ET for corn is typical of the variations previously reported. Interestingly, in both years, the lysimeter with the greatest grain yield also had the largest ET.

Table 4 summarizes the relationships between measured ET for full-cover corn and computed ET. A r_l of 250 s m^{-1} provided a mean ET$_{pm}$ similar to that measured by the lysimeters (the exact match was for r_l = 252 s m^{-1}). The ET$_{pmi}$ performed well (without any fitting, using a corn baseline from Arizona) ($r^2 = 0.98$), but it still underpredicted the measured mean maximum ET (by 16%), although it was the only method for corn not having a significant bias (intercept). The mean r_c value for the ET$_{pmi}$ for the corn was 161 s m^{-1}, and the mean "residual" r_c was 119 s m^{-1}. These differences suggest that the "a" and "b" parameters (eq. 5; table 2) for corn may not be optimum for this environment. All the combination equations over-predicted maximum corn water use (by 5 to 32%), but the Penman (1948) equation predictions were the closest to the measured values (within 5%). The Jensen-Haise equation had a similar mean value (within about 5%) to the mean maximum daily measured ET, but it had a large intercept (bias) and low slope (0.71). Figure 9 shows the fitted Penman-Monteith ET equation compared with the measured ET values for irrigated corn. The $S_{y/x}$ was 0.73 mm d^{-1}, and the measured ET values ranged from less than 3 mm d^{-1} to greater than 12 mm d^{-1}. The ET$_{pm}$ did not fit the few largest measured ET values for corn as well as it did for the wheat or sorghum data sets. It could be related to our methods of interpolating LAI values, but it is most likely due to diurnal effects of winds and vapor pressure deficits.

WIND FUNCTIONS

Fitted wind functions for maximum ET values for the specific crops are summarized in table 5. None of the wind functions fit the data very well, which was similar to the conclusions reported by Steiner et al. (1991) for sorghum. Actually, the wheat wind function is not very different from the original Penman (1948) wind function for grass [$f(U) = 2.63 + 1.42\ U_{2g}$, where U_{2g} is in m s^{-1}]. The slopes were considerably lower than the 2.72 mm d^{-1} kPa^{-1} m^{-1} s reported by Steiner et al. (1991) for sorghum or the 2.31 mm d^{-1} kPa^{-1} m^{-1} s reported by Phene et al. (1986) for grass as well as those used in equations 6 through 8. The inability to fit accurate wind functions may be due to differing daytime and nighttime wind regimes (Pruitt and Doorenbos, 1977; Kizer et al., 1990), VPD, and/or day and nighttime soil water evaporation rates. The relationships between $1/r_a$ and U_{2g} for each crop with r_a estimated following Allen et al. (1989) and Steiner et al. (1991) had much higher coefficients of determination than did the wind functions themselves. The resulting equations are given in table 6. These equations are similar in form to those proposed by McIlroy and Angus (1964) and Thom and Oliver (1977). The more theoretical transfer coefficient was introduced by Van Bavel (1966) and Businger (1956) adopting the adiabatic wind function. It may be considerably simpler to use these $1/r_a$ relationships than the functions used by Allen et al. (1989) to estimate r_a based on the adiabatic wind profile. Mean computed r_a values for these data sets were 32, 27, and 24 s m^{-1} for wheat, sorghum, and corn, respectively. Using the mean 2-m wind speeds (table 2), computed r_a using the empirical $1/r_a$ relationships (table 6) was 28, 24, and 22 s m^{-1} for the wheat, sorghum, and corn.

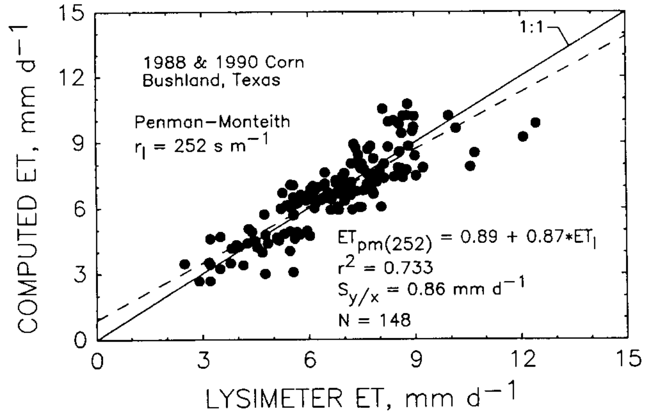

Figure 9–Maximum daily evapotranspiration of irrigated corn at Bushland, Texas, for the 1989 and 1990 growing seasons for days with full-ground cover compared with computed ET by the Penman-Monteith equation with $r_l = 252$ s m^{-1}.

Table 5. Wind function regression results where the intercept is in mm d^{-1} kPa^{-1}, the slope is in mm d^{-1} kPa^{-1} m^{-1} s, and $S_{y/x}$ is in mm d^{-1} kPa^{-1}

Crop	Intercept	Slope	r^2	$S_{y/x}$
Wheat	2.29	1.51	0.406	2.43
Sorghum	1.73	0.51	0.054	2.09
Corn	2.74	0.92	0.223	2.19

Table 6. Regressions results between U_{2g} and $1/r_a$

Crop	Equation	r^2	$S_{y/x}$ (m s^{-1})
Wheat	$1/r_a = 0.00789\ U_{2g}$	0.707	0.00683
Sorghum	$1/r_a = 0.00996\ U_{2g}$	0.812	0.00454
Corn	$1/r_a = 0.00872 + 0.0107\ U_{2g}$	0.792	0.00701

SUMMARY AND CONCLUSIONS

Evapotranspiration rates from irrigated crops of winter wheat, sorghum, and corn were affected strongly by the dynamic environmental conditions experienced in the Southern High Plains. Wheat has a high ET water use because it has a low canopy resistance, grows during a dry, windy part of the year, and has a long growing season. Corn has a similar maximum peak ET rate to sorghum (both are C_4 crops) although sorghum had a slightly smaller canopy conductance ($1/r_c$). Seasonal ET for corn is greater than for sorghum mainly due to the longer growing season for corn and perhaps lower canopy resistance. Seasonal ET for wheat averaged 877 mm while corn and sorghum averaged 771 and 578 mm, respectively, for these seasons. Peak daily ET values for wheat exceeded those for corn or sorghum at this location.

The leaf resistance (r_l) values of 135, 280, and 252 s m^{-1} for wheat, sorghum, and corn, respectively, resulted in matching the mean lysimeter-measured ET using the Penman-Monteith equation. Mean "residual" canopy resistances (r_c) for these maximum ET days were 56, 105, and 119 s m^{-1} for wheat, sorghum, and corn, indicating the considerable difference between the two types of crops (wheat is a C_3 species and sorghum and corn are C_4 species). Other non-stomatal factors (like crop height, LAI, within canopy diffusion resistance, etc.) may also affect both canopy r_c and r_l values. The crop specific (and perhaps location specific) well-watered baseline from Idso (1983) performed rather well in estimating r_c for these crops across a wide range of conditions. It certainly permits a "first time approximate" base value for r_l to be determined quickly and easily. Of course, the apparent differences between maximum crop ET and computed reference ET could be normalized by empirical crop coefficients (Howell et al., 1995c). Wright (1982), Burman et al. (1980), and Jensen et al. (1990) indicate that full cover corn and wheat have ET rates similar to reference alfalfa (peak crop coefficient for alfalfa reference ET for wheat at Kimberly, Idaho, was 1.0 and 0.95 for corn); however, sorghum has not been directly compared with alfalfa. At Davis, California, maximum sorghum ET was 8% more than grass ET (peak crop coefficient for grass reference ET for sorghum was 1.08). Seasonal differences in crop development (Neale et al., 1989) as well as effects of environmental parameters which differentially affect crop and reference ET (Jagtap and Jones, 1989) need further evaluation. It is clear that none of these reference ET equations accurately reflects maximum ET from corn, sorghum, or wheat, except for the Penman-Monteith equation with fitted r_l values or the Penman-Monteith equation using the Idso IRT baseline parameters.

Combination reference ET equations with their traditional wind functions over-predicted maximum crop ET rates at this location because of the higher wind speeds and diurnal wind and vapor pressure deficit patterns. Instantaneous ET equations offer some hope in minimizing these problems (Howell et al., 1995c), but they require additional inputs and perhaps additional complexities (Shuttleworth and Wallace, 1985; Shuttleworth and Gurney, 1990). Simpler ET models using mainly temperature and radiation inputs (Jensen-Haise and Priestley-Taylor) should be used with some degree of caution in this environment as also found by Steiner et al. (1991) because they tend to underestimate maximum ET rates, especially for wheat.

Wind functions could not be developed using the combination ET equation to accurately represent maximum daily ET for sorghum, wheat, or corn. However, rather simple relationships between $1/r_a$ (the transfer coefficient) and daily 2-m wind speed over grass were developed for all the crops with rather strong correlations (from 0.707 to 0.792). This approach offers some potential for using weather station data for predicting the crop aerodynamic canopy resistance for use in the Penman-Monteith equation, but it needs further validation.

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