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Evapotranspiration of Corn -- Southern High Plains

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ABSTRACT

Corn (*Zea mays* L.) has one of the highest evapotranspiration (ET) rates (both daily and seasonally) of all the irrigated crops in the Southern High Plains. ET of fully irrigated corn was measured with precise weighing lysimeters during the 1989, 1990, and 1994 growing seasons at Bushland, TX. In 1994, ET was measured for two different maturity corn hybrids also. Fully irrigated corn achieved a maximum leaf area index (LAI) of 4.5 to 5.5 m^{2} m^{-2} at tassel emergence for the full-season hybrids in each season. LAI was lower for the short-season hybrid in the 1994 season. Crop growth and yields were similar on the lysimeters and the fields and were representative of normal regional corn production. Seasonal ET varied from 744 mm to 901 mm in the three seasons. Daily ET rates often exceeded 10 mm d^{-1}. Peak daily ET rate was not appreciably lower for the short-season hybrid; however, it did have a much smaller seasonal ET but similar water use efficiency as a full-season hybrid. Percolation volumes averaged less than 2% of the total water input (rainfall + irrigation) under the sprinkler irrigation regimes.

Keywords: Dry matter, Irrigation, Leaf area index, Lysimeter, Percolation, Water balance, Water use, Water use efficiency, Yield

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INTRODUCTION

Corn (*Zea mays* L.) is one of the major irrigated crops in the Southern High Plains including the Texas High Plains. Irrigated corn production area averaged 277,400 ha in the 42 county area of the Texas High Plains from 1989 to 1993 with a mean production of 9.48 Mg ha^{-1} (Amosson et al., 1995). Of the major irrigated crops in this region of the U.S., corn has the greatest reported seasonal irrigation requirement (Musick et al., 1990). Irrigated corn has only been grown in the Texas High Plains for about 20 years (a relatively short history compared with sorghum and cotton). Corn is typically produced under moderately high irrigation levels in this region since it is known to be sensitive to water deficits (Musick and Dusek, 1980).

Although much information exists on seasonal corn evapotranspiration (ET) around the world (Rhoads and Bennett, 1990; Doorenbos and Kassam, 1979; Doorenbos and Pruitt, 1977; and Jensen et al., 1990), corn ET has not been accurately measured (Hatfield, 1990) over short-time periods (hours to days) for extended periods (months to seasons) in the Southern High Plains. This area is subjected to regional meso-scale advection (Rosenberg and Verma, 1978) common in the Great Plains of the U.S. The purpose of this paper is to report and summarize daily and seasonal ET measurements using precise weighing lysimeters during three seasons with various corn hybrids.

METHODS AND MATERIALS

The study was conducted at the USDA-ARS Laboratory at Bushland, TX (35° 11' N lat.; 102° 06' W long.; 1,170 m elev. above mean sea level). ET was measured with two weighing lysimeters (Marek et al., 1988) each located in the center of 4.4 ha (210 m E-W by 210 m N-S) fields during the 1989, 1990, and 1994 seasons. Two adjacent (N-S) lysimeter fields were planted in each season. In 1989 and 1990, both fields were planted to the same hybrid and managed similarly. In 1994, one field and lysimeter were planted to a full-season hybrid and the other field and lysimeter were planted to a short-season hybrid. Predominate wind direction is SW to SSW, and the unobstructed fetch (fallow fields or dryland cropped areas) in this direction exceeds 1 km.

Table 1 summarizes the agronomic and management details. Corn was grown on raised beds 0.75 m apart. 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 practices were applied uniformly to the field area. The fields were furrow diked (approximate dike spacing was 1.5 m) in all years to minimize field runoff and rainfall and irrigation redistribution. Irrigations were applied with a 10-span lateral move sprinkler system (Lindsay). The sprinkler system was aligned N-S, and irrigated E-W or W-E. The system was equipped with gooseneck fittings and spray heads (Senninger Super Spray 360°) with medium grooved spray plates on drops located about 1.5 m above the ground and 1.52 m apart. The drops could be converted to LEPA (low energy precision application) heads placed about 0.3 m above the ground. Impact sprinklers (Senninger model 3006) with a 6° discharge angle were also located at 6 m spacing along the lateral move pipeline. The irrigation mode (LEPA, spray, or impact sprinkler) was selected by manual valves. All three sprinkler irrigation modes (impact sprinkler, spray heads, and LEPA) were used at different times during 1989 and 1990 sometimes with differing modes on each lysimeter. In 1994, the system was re-equipped with Nelson spray heads at about 1.8 m above the ground. Irrigations were scheduled to meet the ET water use rate and were typically applied in one to three 25-mm applications per week.

Crop development was measured by periodic plant sampling from 1.5-m^2 areas at sites about 10 to 20 m away from the lysimeters in areas of the field representative of the lysimeter vegetation. LAI and above-ground dry matter (DM) were measured. Final grain yield was measured by harvesting all ears in the lysimeter (9 m^2), and dry matter and grain yield at harvest were measured from adjacent plant samples. 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 load cell scale. Grain samples were obtained from the combined grain and oven dried to determine the moisture content. All grain yield data are reported at 15.5%water content (mass; wet basis).

Table 1. Agronomic and management information.

PARAMETER	UNIT	1989 Full Season	1990 Full Season	1994 Full Season	1994 Short Season
Lysimeter Fields		NE & SE	NE & SE	SE	NE
Previous Crop		Sorghum (FI)	Corn (FI)	Sorghum (LI)	Sorghum (FI)
Hybrid		PIO 3124	PIO 3124	PIO 3245	PIO 3737
Planting	Date	Apr. 26 [116]	May 09 [129]	Apr. 15 [105]	Apr. 15 [105]
Emergence	Date	May 7 [127]	May 18 [138]	May 04 [124]	May 04 [124]
Silking	Date	July 22 [203]	July 26 [207]	July 15 [196]	July 06 [187]
Pollination	Date	Aug. 01 [213]	Aug. 03 [215]	July 25 [206]	July 15 [196]
Physiol. Maturity	Date	Oct. 10 [283]	Sept. 21 [264]	Sept. 06 [249]	Aug. 25 [237]
Harvest	Date	Oct. 24 [298]	Oct. 16 [289]	Sept. 27 [270]	Sept. 16 [259]
Lys. Plt. Dens.	no. m^{-2}	6.0	6.0	8.0	8.0
Field Plt. Dens.	no. m^{-2}	5.9	5.5	7.8	8.5
Fertility	g(N) m^{-2}				
NH_4		16	25	26	26
Liquid (10-34-0)		0	0	3	3
Furrows Diked	Date	June 22 [173]	June 19 [170]	June 01 [152]	June 01 [152]

FI indicates previous crop was fully irrigated. LI indicates previous crop received limited irrigation (50%of FI).

Numbers in brackets indicate day of year.

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; and Howell et al., 1995c) with an irrigated grass surface (cool-season lawn mixture containing bluegrass, perennial rye-grass, etc.).

Soil water contents were measured periodically (about 2 week intervals) using a neutron probe (Campbell Pacific model 503DR Hydroprobe) at 0.2-m depth increments with 15-s counts. Two access tubes were located in each lysimeter (read to 1.9-m depth) and four tubes were located in the field surrounding each lysimeter (read to 2.3-m depth). The probe was field calibrated for the Pullman soil using a method similar to that described by Evett and Steiner (1995).

Lysimeter mass was determined using a Campbell Scientific CR-7X data logger to measure and record the lysimeter load cell (Alphatron S50 in 1989 and 1990 and Interface SM-50 in 1994) signal at 0.5-Hz (2 s) frequency. The load cell signal was averaged for 15 min and composited to 30-min means. 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 the 9.00 m^2 inside area). This correction is applicable for full-cover crops, but it would not be necessary apply for bare soil conditions. Nevertheless, it was applied to all data uniformly.

RESULTS

Climate and Crop Data

The climatic conditions during the three seasons are summarized in Table 2. Rainfall was 39% above normal in 1989, 33% below normal in 1990, and 8% below normal in 1994 for the April through September corn season. Late May through early July in 1990 experienced very dry and hot conditions. The Southern High Plains has a characteristically variable climate not unlike the range demonstrated during these three seasons. Hail (25-mm dia.) received on 17 May 1989 essentially beat the above-ground plants back to ground level; however, the crop recovered and appeared to grow normally. Of particular importance is the consistently high wind speed at Bushland (monthly mean 2-m wind speed was never less than 3.0 m s^{-1}).

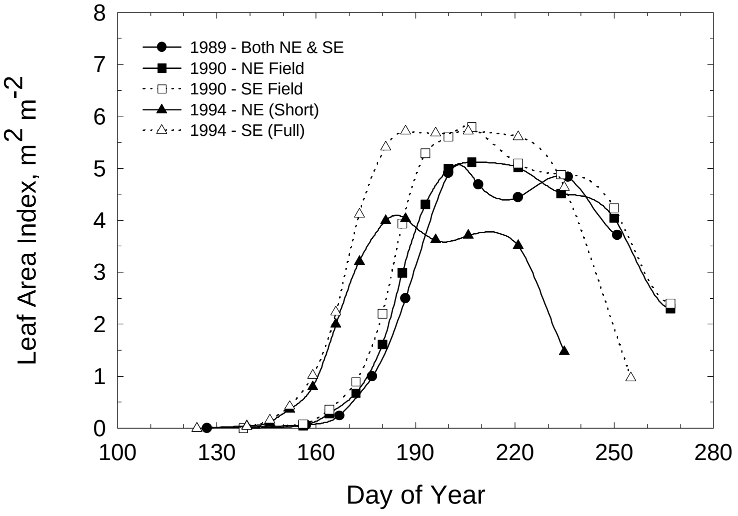

Figure 1. Leaf area index for fully irrigated corn in the lysimeter fields for the three growing seasons.

Seasonal trends in leaf area index (LAI) are shown in Fig. 1. The 1989 and 1990 data are similar, but the 1994 data are different owing to the earlier planting date (2 to 3 weeks) and the different hybrids. In each season, the full-season hybrid had maximum LAI between 4.9 m^2 m^{-2} (1989) and 5.7 m^2 m^{-2} (1994) occurring just at or before tassel emergence. The crop grew uniformly in both the lysimeters and the fields in 1989; however, in 1990, the SE field and lysimeter crops grew more vigorously than the NE field and lysimeter. These differences were reflected in the LAI, yield, and ET (to be discussed in next section). However, LAI differences between the two fields were rather small (< 0.95 m^2 m^{-2} and more typically < 0.6 m^2 m^{-2}). Dry matter and crop height data (not shown) followed similar trends in 1990. Most notable is the difference in LAI in 1994 for the two different hybrids. The short-season hybrid LAI peaked a few days before the full-season hybrid due to the shorter period to tassel emergence. However, the main, and most important difference, was in the LAI magnitude varying from a peak of 4.0 m^2 m^{-2} for the short-season hybrid to over 5.7 m^2 m^{-2} for the full-season hybrid and the longer period of near peak LAI for the full-season hybrid. Dry matter was also lower along with the crop height for the short-season hybrid in 1994.

Table 2. Summary climatic data for corn growing seasons at Bushland, TX.

PARAMETER	UNIT	April	May	June	July	August	September
** 1989 **							
Mean Max. Temp.	°C	23.1	28.5	26.7	30.9	29.4	25.7
Mean Min. Temp.	°C	5.7	13.5	14.1	16.5	16.6	11.1
Mean Dew Point Temp.	°C	-0.2	9.2	13.2	12.9	14.8	8.9
Mean Solar Rad.	MJ m^{-2} d^{-1}	23.0	23.1	23.4	26.3	21.2	19.0
Mean PFD	mol m^{-2} d^{-1}	45.6	46.5	47.4	53.3	43.6	38.6
Mean 2-m Wind Speed	m s^{-1}	4.8	5.4	5.1	3.4	3.3	3.3
Mean Atms. Pressure	kPa	87.2	87.1	87.3	88.1	88.5	88.7
Total Rainfall	mm	15	111	118	81	104	67
** 1990 **							
Mean Max. Temp.	°C	20.3	25.3	36.2	30.3	31.0	27.9
Mean Min. Temp.	°C	5.2	8.6	17.4	16.9	16.2	14.5
Mean Dew Point Temp.	°C	2.9	0.2	9.4	12.1	12.2	10.5
Mean Solar Rad.	MJ m^{-2} d^{-1}	21.8	25.2	28.8	25.1	23.3	17.2
Mean PFD	mol m^{-2} d^{-1}	43.1	49.3	57.6	51.3	47.4	35.1
Mean 2-m Wind Speed	m s^{-1}	5.2	5.2	5.5	4.5	3.3	2.6
Mean Atms. Pressure	kPa	88.2	88.6	91.3	90.2	89.3	89.3
Total Rainfall	mm	18	20	5	78	44	73
** 1994 **							
Mean Max. Temp.	°C	20.9	24.9	33.3	31.3	30.7	28.6
Mean Min. Temp.	°C	3.8	11.5	16.8	17.2	16.4	12.4
Mean Dew Point Temp.	°C	0.1	10.6	12.5	14.5	14.5	9.5
Mean Solar Rad.	MJ m^{-2} d^{-1}	20.5	21.2	25.8	25.9	21.4	19.4
Mean PFD	mol m^{-2} d^{-1}	43.0	44.0	55.2	49.7	44.7	39.3
Mean 2-m Wind Speed	m s^{-1}	5.3	4.5	3.6	3.1	3.1	3.6
Mean Atms. Pressure	kPa	88.8	89.0	88.9	89.1	89.2	89.2
Total Rainfall	mm	35	49	35	109	61	41
Historical Means							
Max. Temperature	°C	21.1	24.9	30.2	32.1	31.0	27.3
Min. Temperature	°C	3.9	9.3	14.8	16.9	16.2	11.7
Solar Radiation	MJ m^{-2} d^{-1}	22.5	24.4	26.3	25.6	22.8	19.2
Total Rainfall	mm	26	68	78	65	71	49

20-yr means.

Table 3. Crop yield and seasonal water balance summary (based on planting to harvest periods). Field values were averaged for the 1989 and 1990 data since hybrids were the same on both fields.

		1989			1990			1994			
PARAMETER	UNIT	NE	SE	Field	NE	SE	Field	SE	Field	NE	Field
Grain Yield	g m^{-2}	1237	1194	1172	1148	1327	1313	1564	1692	1337	1340
Dry Matter Yield	g m^{-2}	2168	2175	2098	2127	2177	2420	2426	2638	2035	1987
Combine Yield	g m^{-2}	na	na	976	na	na	1096	na	1354	na	1081
Harvest Index	---	0.48	0.46	0.47	0.46	0.52	0.46	0.54	0.54	0.56	0.57
Emg. SW Content	m^3 m^{-3}	0.29	0.26	0.29	0.31	0.28	0.28	0.26	0.26	0.31	0.29
Hrv. SW Content	m^3 m^{-3}	0.30	0.28	0.27	0.28	0.29	0.28	0.29	0.26	0.32	0.30
Irrigation §	mm	282	241	same	578	618	same	577	same	465	same
Rainfall V	mm	484	484	same	224	224	same	320	same	319	same
Evapotranspiration	mm	814	744	na	783	829	na	901	na	783	na
Profile Drainage #	mm	44	0	na	6	0	na	0	na	30	na
Grain WUE	kg m^{-3}	1.41	1.36	na	1.24	1.35	na	1.47	na	1.44	na
DM WUE	kg m^{-3}	2.66	2.92	na	2.72	2.63	na	2.93	na	2.60	na

Mean profile (2.3 m for field and 1.9 m for lysimeters) soil water content near emergence.
Mean profile (2.3 m for field and 1.9 m for lysimeters) soil water content near harvest.
§ Based on lysimeter mass gain following irrigations.
V From weather station rainfall.
\# Determined by drainage from lysimeter monolith.
Dry grain yield per unit ET (planting to harvest).
DM yield per unit ET (planting to harvest).

Grain and dry matter yields (Table 3) again indicated the close correspondence between the lysimeters and fields. Grain yield ranged from 1148 g m^{-2} (NE lysimeter in 1990) to over 1690 g m^{-2} (SE field in 1994). Lysimeter yields were no lower than 87% of the field average (NE in 1990) or greater than 6% above the field average yield (NE in 1989). Field mean combine yields ranged from 976 g m^{-2} in 1989 to over 1354 g m^{-2} with the full-season hybrid in 1994. These yields are comparable to the 1989-1993 mean Texas High Plains yield for corn of 948 g m^{-2} (Amosson et al., 1995) and representative for this region. Also, the yield difference of 200 to 350 g m^{-2} of grain between the full-season and short-season hybrids should be noted. Differences between the lysimeters and the field dry matter yield were typically less than 12%. Harvest index (dry grain yield per unit dry matter) averaged 0.52 for all the seasons, hybrids, and fields.

Daily ET Rates

ET rates for the three seasons are shown in Fig. 2 through 4. The 1989 season had few extreme ET events compared with the other two seasons. In 1989, ET rates exceeded 10 mm d^{-1} only on a few days (Fig. 2). In 1990, ET rates exceeded 10 mm d^{-1} on several days in mid to late June to early July [DOY 170 to 185] (Fig. 3). In 1994, several days had ET rates exceeding 10 mm d^{-1} with a maximum slightly exceeding 14 mm d^{-1} for both maturity hybrids (Fig. 4). Daily ET rates were typically low before about the 4-6 leaf stage unless the soil surface was wetted by either irrigation or rainfall. ET rates were typically in the 6 to 10 mm d^{-1} range after maximum ground cover was established. Daily ET rates with full ground cover remained rather consistent until about mid-grain fill (dent stage) when rates began to decline with senescence due to loss of green leaf area and leaf aging.

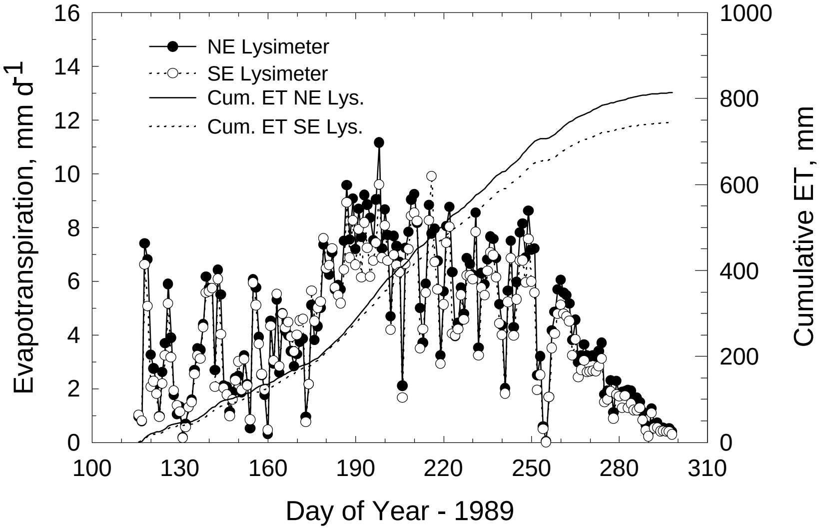

Figure 3. ET for fully irrigated corn (full-season hybrid) at Bushland, TX in 1989.

In 1990, the SE lysimeter ET exceeded the NE lysimeter rather consistently throughout the season (Fig. 3). Most of the difference in ET rates in 1990 can be explained by the taller crop and larger LAI (Fig. 1) on the SE field. We suspect that part of the difference may have been due to local advection where the SE lysimeter has less fetch (100 m of exactly the same cropping condition) than the NE lysimeter (300 m) in the predominate wind direction. In 1989, the two lysimeter ET values were nearly equal at tassel emergence, and then the NE lysimeter slightly exceeded the SE lysimeter until the dent growth stage. Additionally, part of the differences between the two lysimeters within a year may be attributed to the *effective* area of the individual lysimeter (see Ritchie et al., 1996 in this proceedings) caused by differing plant growth on and immediately surrounding the lysimeters that may not have visually obvious.

In 1994 with the different hybrids, both lysimeters had similar ET values until about DOY 175 (Fig. 4) when the two hybrids began to differ in LAI (Fig. 1). From DOY 175 to 225, the full-season hybrid ET was consistently 8 to 15% larger than the short-season hybrid ET. At DOY 225, which corresponded to dent for the early season hybrid, the ET rate for the short-season hybrid continuously declined in

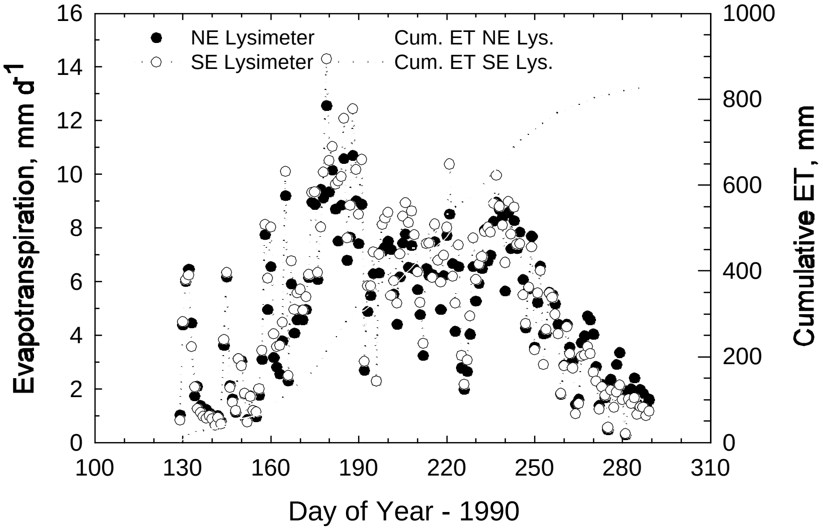

Figure 2. ET for fully irrigated corn (full-season hybrid) at Bushland, TX in 1990.

proportion to the full-season hybrid ET (Fig. 4) until DOY 250 when the full-season hybrid reached physiological maturity. Short-season corn did not appreciably reduce (<5%) peak daily ET rates despite its lower LAI and shorter height.

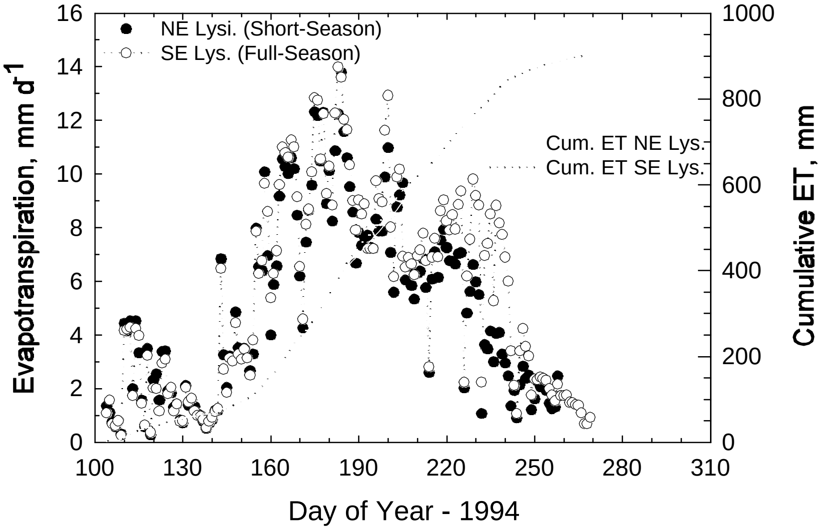

Figure 4. ET of fully irrigated corn at Bushland, TX in 1994. NE lysimeter has a short-season hybrid, and SE lysimeter had a full-season hybrid.

Water Balance for Irrigated Corn

Table 3 provides a summary of the lysimeter and field water balance data for these three seasons. Irrigations were scheduled to minimize soil water deficits; however, some soil water differences existed between the lysimeters and the field (Table 3). Generally, the lysimeters did not have a major depletion of soil water during the seasons, except for the NE lysimeter in 1990 which had a greater depletion than the SE lysimeter. Also the NE lysimeter caught less irrigation water possibly because of differing irrigation methods that were used (alternatingly) on the two lysimeters. Short-term (a few days) water deficits may have occurred in both 1989 and 1990 on the SE and NE lysimeters, respectively, as indicated by the soil water data and yield data. In 1994, both fields were irrigated exactly the same until the NE field reached the dent stage when irrigations were terminated on that field.

Lysimeters measure the net balance of rainfall and irrigation applications, hence separate measurements must be made of each to fully account for all water. However, point irrigation application amounts are difficult to accurately determine with moving irrigation machines. Table 3 presents "net" irrigation catches by the lysimeters. Rainfall data in Table 3 were recorded at the weather station site (< 300 m away).

The SE lysimeter never drained during these seasons; however, the NE lysimeter had some modest drainage volumes (6 to 44 mm) over these seasons. Drainage events typically occurred following large rainfall events (> 40 to 60 mm) when the soil water was relatively full from irrigation. Percolation through the Pullman clay loam profile has long been assumed to be negligible due to the slow permeability of the B22 horizon, but we have consistently observed between 1 to 5% of the total received water (rainfall + irrigation) to percolate through the Pullman profile under fully irrigated conditions. We seldom observe significant percolation from dryland production systems. Since these fields were furrow diked, minimal field runoff occurred and was mainly limited to the time from planting until dike installation. Irrigations never created any field runoff. Part of the lysimeter percolation volume could be attributed to runoff since the lysimeters impound about 25 to 40 mm of rainfall without overtopping.

Seasonal ET varied from 744 mm (SE lysimeter in 1989) to 901 mm (SE field in 1994). These values are consistent with previous soil water balance estimates for fully irrigated corn at

Bushland (Musick and Dusek, 1980; Eck, 1984; Howell et al., 1989; Howell et al., 1995b). Fully irrigated corn needs about 400 to over 600 mm of seasonal irrigation to avoid critical water deficits to achieve high production levels in this region. These seasonal ET values are somewhat more than ET values reported for northern Great Plains locations (Hattendorf et al., 1988; Stegman, 1982) where vapor pressure deficits and wind are lower. The field sizes (4 ha) should have largely minimized local advection, but it is possible that the greater ET rates could be partially attributed to an *oasis* effect. But we believe that climate influences (wind and vapor pressure deficit) were more dominate than *localized advection.*

Water Use Efficiency

Water use efficiency (WUE; dry yield per unit ET) varied from 1.24 kg m^{-3} (NE in 1990) to 1.47 kg m^{-3} (SE in 1994) and averaged 1.38 kg m^{-3} for all the lysimeter. Corresponding DM water use efficiency values varied from 2.60 kg m^{-3} (NE in 1994) to 2.92 kg m^{-3} (SE in 1989) and averaged 2.75 kg m^{-3} for all lysimeters. These values are somewhat lower than means reported by Tanner and Sinclair (1983), but are similar to WUE values for other C_4 crops (Stanhill, 1986).

CONCLUSIONS

Corn has high seasonal and daily water use rates in the Southern High Plains compared with more moderate climates in the northern Great Plains or other semi-arid locations in the western U.S. without consistently high winds. Daily ET rates often exceeded 10 mm d^{-1} for significant time periods. These high ET rates for corn and the widely known sensitivity of corn to soil water deficits, indicate that deficit irrigation (or low irrigation capacity) of corn should be avoided in this region to reduce production risks resulting from inadequate rainfall as supported by Musick and Dusek (1980) and Howell, et al. (1989; 1995b). Irrigated corn consistently produced a grain WUE averaging 1.4 kg m^{-3} and a dry matter WUE averaging 2.7 kg m^{-3} in this environment for the hybrids used.

Irrigated corn LAI ranged from about 4.5 to 5.5 m^2 m^{-2} for these hybrids and plant densities. A short-season corn hybrid reduced LAI, dry matter, and grain yield compared with a full-season hybrid in 1994, but it produced nearly equal grain WUE while decreasing seasonal ET amount by almost 120 mm. Short-season corn, however, did not appreciably reduce the peak daily ET rate.

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