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Evapotranspiration and Yield of Corn Grown on Three High Plains Soils

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ABSTRACT

Soil properties that vary within a production area present management challenges to producers when water supplies are limited. We conducted three experiments to determine the influence of soil type and different water management levels on corn (*Zea mays* L.) yield, evapotranspiration (ET), and water use efficiency. Short-season corn was grown at low population density in lysimeters containing monolithic soil cores of Pullman (fine, mixed, superactive, thermic Torrertic Paleustoll), Ulysses (fine-silty, mixed, superactive, mesic Aridic Haplustoll), and Amarillo (fine-loamy, mixed, thermic Aridic Paleustalf) soils, at a rain shelter facility in Bushland, TX. Dryland conditions were simulated in 1994 and 1995, with the soils receiving irrigations totaling either 50 or 150 mm in 1994 and either 120 or 200 mm in 1995. In 1996, water management levels were expanded, with the soils receiving weekly irrigation equivalent to 20, 50, 80, and 110% of measured ET. Grain yields for the 3 yr ranged from 389 to 804 g m^{-2} for the Pullman soil, 559 to 899 g m^{-2} for the Ulysses soil, and 438 to 736 g m^{-2} for the Amarillo soil. Low grain yields from corn in the Pullman soil were due to limited water extraction from the lower soil profile. Even under full irrigation (110%), grain yield and leaf area were lower for corn in the Amarillo soil than with the two other soils, possibly due to limited water availability. Soil type effects on corn water use and yield may require different water management strategies for optimum water use efficiency.

Corn (*Zea mays* L.) is a major irrigated crop in the southern and central High Plains of the USA (Musick et al., 1990), with a high seasonal water requirement for maximum yields (Musick and Dusek, 1980). The High Plains have a high evaporative demand environment, with limited rainfall. Howell et al. (1997) reported maximum measured evapotranspiration (ET) rates of 12.4 mm d^{-1} for irrigated corn at Bushland, TX. Important soil series in the southern High Plains region include the Pullman (Unger and Pringle, 1981; NRCS, 1998a) and the Amarillo (Burnett et al., 1962), and in the central High Plains region the Ulysses (Musick and Sletten, 1966; NRCS, 1998b).

Maximum grain yields have been obtained through supplemental irrigation from the Ogallala aquifer, where water levels are declining. The limited available water requires that irrigation be used as efficiently as possible. Because of its reduced water requirements, short-season corn has become increasingly popular in the region (Howell et al., 1998).

Corn production systems that are successful in one location may be unsuccessful in another, due to differences in such factors as management practices, cultivar selection, rainfall amounts, evaporative potential, initial soil water contents, and soil hydraulic characteristics. For these reasons, grain yields can vary at the same location from year to year. For example, in the southern High Plains, Musick and Dusek (1980) reported a maximum full-season corn grain yield for the Pullman soil of 975 g m^{-2}, which was produced with 400 mm of irrigation, 230 mm of precipitation, and 667 mm ET. In that same experiment, the treatment that received 80 mm of irrigation produced no yield with 391 mm ET. Howell et al. (1995) obtained 1550 g m^{-2} corn grain yield with 644 mm irrigation, 227 mm precipitation, and 973 mm ET at the same location in a different cropping season. Their dryland irrigation treatment yielded 400 g m^{-2} grain with 227 mm precipitation and 383 mm ET. The climate for both seasons was described as near normal. Interestingly, the grain water use efficiency for the fully irrigated treatments in those studies was similar (at 1.27 g m^{-3} and 1.35 kg m^{-3} in the two respective seasons) for dry grain with different cultivars and irrigation methods.

The 10-yr mean grain yield of fully irrigated corn reported by Schlegel and Havlin (1995) for a Ulysses silt loam in the central High Plains was about 1110 g m^{-2}. Individual year production ranged from about 840 to 1330 g m^{-2}. Grain yield of deficit-irrigated corn in a Keith silt loam (Aridic Argiustoll), a soil series similar to the Ulysses series, was 780 g m^{-2} with 324 mm precipi-

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Abbreviations: DOY, Day of Year; ET, evapotranspiration; ET_o, reference evapotranspiration; HI, harvest index; LAI, leaf area index; LL, lower limit of water extraction; PAW, plant available water; RMSE, root mean square error.

Table 1. Agronomic and growth stage information.

	1994	1995	1996
Hybrid	PIO-3737	PIO-3737	PIO-3737
Row spacing, m	0.75	0.75	0.75
Population, plant m^{-2}	4	4	5.3
N–P fertilization, g m^{-2}	11–6	14–6	18–4
Growth stage			
Planting	21 Apr. (111)†	10 May (130)	23 May (143)
Emergence	5 May (125)	22 May (142)	3 June (155)
Anthesis	1 July (182)	22 July (203)	22 July (204)
Harvest	18 Aug. (230)	8 Sept. (251)	5 Sept. (249)

† Numbers in parentheses are Day of Year.

tation in one year and 640 g m^{-2} with 352 mm of precipitation in the next year, both receiving 75-mm in irrigation (Lamm et al., 1993).

In modeling the effects of soil depth and climatic factors on corn yield, Swan et al. (1987) found a significant interaction effect on grain yield between climate and soil water-holding capacity. Gardner (1983) noted that a combination of plant, soil, and atmospheric factors controls efficient water use. He cautioned that if water is to be efficiently utilized, each crop–soil combination must be considered separately. Based on 4 yr of data in conventionally tilled fields in Indiana, Griffith et al. (1973) showed that grain yield reductions were 16% for corn grown in a silty clay and 3% for corn grown in a sandy loam compared with yields from a silt loam.

Musick and Dusek (1980) advised that limited irrigation of corn should not be practiced in the high evaporative demand environment of the southern High Plains, due to the sensitivity of corn to water stress. They analyzed published relationships between yield and ET and concluded that grain yield reductions associated with reduced water application were less severe in (i) deep soils with high water storage capacities, where roots can extend into the moist subsoil, (ii) irrigation strategies that distribute stress throughout the season, and (iii) lower evaporative demand environments.

An understanding of the interaction between soil, plant, and climatic factors is important in obtaining maximum efficient water use. The objective of this research was to determine how much, if any, soil characteristics affect short-season corn yield, water use, and water use efficiency in a range of soil water contents by evaluating crop response under identical climatic conditions and with similar management practices.

MATERIALS AND METHODS

The study was conducted in three experiments (1994–1996) at Bushland, TX, in a 0.25-ha field with a rain shelter facility that has 48 weighable lysimeters that contain three different soil series. The corn used in the study was a short-season hybrid (PIO-3737)[1] reaching maturity in approximately 100 d. Planting was delayed in 1996 due to the installation of a subsurface drip system for the area surrounding the lysimeter facility. The plant populations used in the three experiments represent populations more typical of dryland to limited-irrigation studies (Olson, 1971). Agronomic and growth stage information for the 3 yr is summarized in Table 1.

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

Table 2. Soil descriptions by horizon for the three soil series used in lysimeter experiments at Bushland, TX (1994–1996).

Horizon†	Depth	Texture	Sand	Silt	Clay	Bulk density
	m			%		Mg m^{-3}
Pullman series (fine, mixed, superactive, thermic Torrertic Paleustoll)						
Ap	0.0–0.18	cl	20.4	49.3	30.3	1.35
Bt1	0.18–0.46	sicl	17.2	45.2	37.6	1.44
Bt2	0.46–0.74	sicl	18.1	44.7	37.2	1.50
Bt3	0.74–1.02	cl	20.3	42.8	36.9	1.47
Bt4	1.02–1.35	cl	22.9	41.0	36.1	1.55
Bk1	1.35–1.98	c	18.1	39.7	42.2	1.42
Bk2	1.98–2.29	sicl	19.5	44.0	36.5	1.41
Ulysses series (fine-silty, mixed, superactive, mesic Aridic Haplustoll)						
Ap	0.0–0.13	cl	21.9	49.1	29.0	1.45
A	0.13–0.25	cl	21.9	47.9	30.2	1.42
Bw	0.25–0.46	sicl	12.0	54.1	33.9	1.42
BC	0.46–0.71	sicl	14.4	55.8	29.8	1.38
C1	0.71–1.02	sil	24.8	55.2	20.0	1.47
C2	1.02–2.20	sic	19.1	40.8	40.1	1.37
Amarillo series (fine-loamy, mixed, thermic Aridic Paleustalf)						
Ap	0.0–0.23	fsl	73.7	12.3	14.0	1.73
Bt	0.23–0.58	scl	61.1	16.3	22.6	1.70
Btk1	0.58–0.84	scl	58.0	15.3	26.7	1.65
Btk2	0.84–1.40	scl	58.8	16.5	24.7	1.66
Btk3	1.40–2.03	scl	53.5	20.2	26.3	1.69
Btk4	2.03–2.20	cl	40.9	31.4	27.7	1.71

† Horizon modifiers: p indicates plowing or other disturbance; t indicates illuvial clay (translocated silicate clay); k indicates calcic horizon; w indicates development of color or structure but with little illuvial accumulations.

The lysimeters are 1.0 by 0.75 m, and 2.3 m deep, and contain monolithic soil cores to a 2.2-m depth. A suction drainage system was installed in the bottom 0.1 m. Lysimeters were arranged in two pits, with each pit containing two side-by-side rows of 12 lysimeters each. Eighteen lysimeters were used in the 1994 and 1995 experiments and 36 lysimeters in 1996. The remaining lysimeters were used in associated studies at the facility. Soil series were randomly located within each pit, with three replications per soil type.

The rain shelter used was a metal building 13 by 18 m by 3.7 m high, with a control sensor that automatically initiates building movement over the lysimeters when the sensor detects about 1 mm of rain. The facility and monolithic core collection techniques were described in more detail by Schneider et al. (1993).

Soils

Soil types were Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll) from Bushland, TX; Ulysses clay loam (fine-silty, mixed, superactive, mesic Aridic Haplustoll) from Garden City, KS; and Amarillo sandy loam (fine-loamy, mixed, superactive, thermic Aridic Paleustalf) from Big Spring, TX (Table 2). The Pullman series consists of deep, well-drained, very slowly permeable soils that formed in calcareous clayey materials with a moderate to high water-holding capacity, depending on the depth to the caliche layer. The Ulysses series consists of very deep, well-drained, moderately permeable upland soils that formed in calcareous loess with a high water-holding capacity. The Amarillo series consists of deep, well-drained, moderately permeable soils that formed in calcareous loamy materials and have a moderate water-holding capacity. The typical Ulysses soil is classified as a silt loam, but slightly lower silt contents in the surface layers resulted in their designation as a clay loam. This is within the allowable variation of the series. Textural analyses were obtained from a commercial testing laboratory (Servi-Tech Laboratory, Dodge City, KS), using samples taken at the lysimeter collection sites.

Table 3. Cumulative evapotranspiration (ET), soil water depletion (Depl.), irrigation amounts, grain and biomass yield components, harvest index (HI), seed mass and seed number, and grain and biomass water use efficiency (WUE) of corn grown in lysimeter experiments at Bushland, TX (1994–1996).

Main effect					Yield			Seed		WUE¶	
Soil	Tmt.	ET	Depl.‡	Irr.	Grain§	Biomass	HI	Mass	Number	Grain	Biomass
		mm			g m^{-2}		%	mg seed^{-1}	no. m^{-2}	kg m^{-3}	
							1994				
Pullman	I-25	400e#	207c	50	594bc	1107cd	54bc	256a	2327d	1.49abc	2.77a
Ulysses	I-25	511b	321a	50	797a	1413ab	56ab	234a	3419b	1.56ab	2.77a
Amarillo	I-25	429de	305ab	50	578c	1100d	53c	244a	2378d	1.35c	2.56a
Pullman	I-75	449cd	187c	150	665bc	1206cd	55abc	244a	2720cd	1.48bc	2.69a
Ulysses	I-75	556a	283ab	150	899a	1543a	58a	233a	3865a	1.62a	2.78a
Amarillo	I-75	485bc	272b	150	689b	1281bc	54bc	238a	2887c	1.42bc	2.64a
LSD (0.05)		43	48		108	175	4	29	437	0.15	0.22
							1995				
Pullman	I-60	370ab	98cd	125	389c	866c	45b	232ab	1678c	1.05b	2.34b
Ulysses	I-60	406ab	221a	125	559ab	1169a	48ab	256a	2192a	1.38a	2.88a
Amarillo	I-60	360ab	185ab	125	438bc	920bc	48ab	209b	2098abc	1.22ab	2.56ab
Pullman	I-100	353b	49d	200	433cd	864c	50a	247ab	1739a	1.23ab	2.45b
Ulysses	I-100	433a	154bc	200	578a	1141ab	51a	247ab	2340a	1.33a	2.64ab
Amarillo	I-100	424ab	176ab	200	564ab	1126ab	50a	259a	2170bd	1.33a	2.66ab
LSD (0.05)		77	64		134	244	4	40	435	0.24	0.40
							1996				
Pullman	I-20	328g	151de	143	499e	983f	51b	230e	2178e	1.52abcd	3.00ab
Ulysses	I-20	401f	248a	145	655a	1293de	51ab	234e	2804bcd	1.63a	3.22a
Amarillo	I-20	342g	215b	128	536e	983f	55a	214f	2498ab	1.57ab	2.87b
Pullman	I-50	446e	121ef	308	684cd	1308de	52ab	242cde	2825bcd	1.53ab	2.93b
Ulysses	I-50	507cd	191bc	314	785abc	1519abc	52ab	240de	3289ab	1.55ab	3.00b
Amarillo	I-50	436e	173cd	271	670d	1248e	54a	234e	2868bcd	1.54abc	2.86bc
Pullman	I-80	527c	48h	467	790ab	1520abc	52ab	257abc	3075abc	1.50abcd	2.88bc
Ulysses	I-80	569b	93fg	475	808ab	1570ab	51ab	258ab	3121abc	1.42bcde	2.76bcd
Amarillo	I-80	496d	88g	408	716bcd	1393cde	51ab	262a	2738a	1.44bcde	2.81bcd
Pullman	I-110	610a	0i	629	804ab	1590ab	51ab	258ab	3107abc	1.32e	2.61d
Ulysses	I-110	617a	−20i	639	847a	1648a	51ab	251abcd	3369a	1.37de	2.67cd
Amarillo	I-110	534c	−12i	548	736bcd	1426bcd	52ab	245bcde	3012abc	1.38cde	2.67cd
LSD (0.05)		30	30		104	169	3	15	487	0.16	0.24

† ET is calculated as the change in lysimeter mass between Day of Year (DOY) 138 and DOY 242 in 1994, DOY 142 and DOY 254 in 1995, and DOY 162 and DOY 249 in 1996, plus any irrigation or rainfall and minus any drainage.
‡ Depletion is the change in soil water content for a 2.2-m profile as measured by neutron scattering between DOY 136 and DOY 243 in 1994, DOY 142 and DOY 254 in 1995, and DOY 156 and DOY 250 in 1996.
§ Grain is reported on a dry basis.
¶ Ratio of yield (dry basis) to ET.
\# Main effect means followed by a different letter are significantly different within the main effect at the 0.05 probability level, and are determined for each soil type–irrigation combination as an individual treatment within each year.

Plant available water (PAW, in mm) is the water in the soil available for plant use, with the lower limit of this availability defined as the soil water content at which plants can no longer extract water or regain turgor and subsequently die (Ratliff et al., 1983). For these experiments, PAW was calculated as the water remaining in a 2.2-m profile above the lower limit of water extraction (LL) determined for grain sorghum [*Sorghum bicolor* (L.) Moench] by neutron scattering (NS) measurements in a prior experiment (data not reported here). An experiment on corn had not been performed at the facility, but water extraction by corn and grain sorghum has been considered to be similar by Stewart et al. (1975) and Ratliff et al. (1983). The lower limits determined in this study were comparable to other measured LL values for soils representative of the Pullman series and the Ulysses series reported by Ratliff et al. (1983). The Amarillo soil's LL value was 34% higher than that reported by Ratliff et al. (1983), possibly due to the clay in the deep soil layers (Table 2).

Irrigation Treatments

Irrigation treatments were selected to test plant response to a range of water stress with different climatic environments (years). The rain shelter permitted management of water applications so that simulated dryland studies could be evaluated in 1994 and 1995, and ET replacement irrigation management in 1996, both without confounding effects due to rainfall. In 1994 and 1995, irrigations were timed so that the crop could receive supplemental irrigation at critical growth stages as increments of normal rainfall (Musick and Dusek, 1980). In 1996, the study was expanded to provide a broader range of irrigation treatments with additional lysimeters that would allow stress to develop through the season. Plant population was increased as well from the 4 plant m^{-2} used in 1994 and 1995 to 5.3 plant m^{-2} to be more representative of limited to fully irrigated corn populations (Musick and Dusek, 1980; Howell et al., 1995). Irrigations were measured and manually applied, and application amounts for the three experiments are summarized in Table 3.

In 1994, irrigation treatments were equivalent to 25% (I-25) and 75% (I-75) of the normal rainfall of 200 mm (Howell et al., 1995) for the cropping period (mid-May through mid-August). The PAW at emergence was about 270 mm in the Pullman soil, about 400 mm in the Ulysses soil, and about 320 mm in the Amarillo soil. The I-75 treatment received a 50-mm irrigation at emergence, mid-vegetative, and pollination growth stages. The I-25 treatment received an 50-mm irrigation at the mid-vegetative growth stage. All lysimeters received an additional 12 mm of water on DOY 179 and 9 mm on DOY 193, when the rain shelter failed to close.

In 1995, irrigation treatments were 60% (I-60) and 100% (I-100) of normal rain, with each soil type and irrigation treatment containing about 280 mm PAW at emergence. Initial

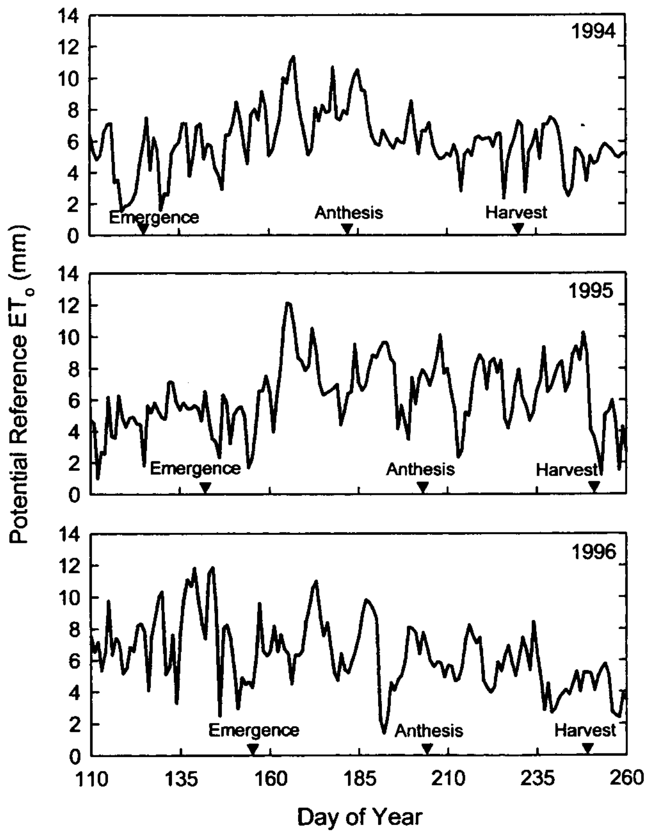

Fig. 1. Grass reference evapotranspiration (ET_o) at Bushland, TX, for the three study years, with cropping season dates for corn.

soil water contents were changed from those in 1994 so that the crop in the Ulysses soil would begin the growing season with PAW equivalent to that in the Pullman and the Amarillo soils. The I-60 treatment received a 50-mm irrigation at the 8-leaf and mid-grain-fill growth stages, and a 25-mm irrigation at tasseling. The I-100 treatment received a 50-mm irrigation at the 8-leaf, early grain-fill, and mid-grain-fill growth stages, and a 25-mm irrigation at tasseling and pollination.

The 1996 irrigation treatments were 20% (I-20), 50% (I-50), 80% (I-80), and 110% (I-110) replacement of ET as measured for the I-110 treatment of each soil type. Each soil type and irrigation treatment had about 250 mm PAW at emergence. Soil water content was measured by neutron scattering (Model 503 DR, Campbell Pacific Nuclear, Martinez, CA) at depth increments of 0.2 m, starting at 0.1 m and ending at 2.1 m. The gauge was calibrated in situ at the Garden City, Big Spring, and Bushland monolith collection sites, using techniques described by Evett and Steiner (1995). Separate calibration equations were developed for the A, Bt, and Bk horizons of the Pullman soil; the A, Bt, and Btk horizons of the Amarillo soil; and the A and B horizons of the Ulysses soil.

Evapotranspiration

Evapotranspiration was calculated from lysimeter mass changes measured weekly either with a load cell (Model 600001A-10K, Sensortronics, Covina, CA) connected to a datalogger (CR-7, Campbell Scientific, Logan, UT), or by deck scale (DS-30x40-10K, Weigh-Tronix, Fairmont, MN) as the difference in mass between readings, plus any applied water minus any drainage water. The lysimeters were drained from the bottom each year prior to planting with a vacuum pump operating at 0.06 MPa vacuum, and were checked for drainage during the cropping season. Potential grass reference ET (ET_o) was calculated from procedures outlined by Allen et al. (1989), using instrumentation located at a nearby weather station.

Leaf Area Index

Leaf area index (LAI) was measured only on the 1996 I-110 irrigation treatment due to time and labor constraints. Leaf area for each lysimeter was estimated as the sum of the products of the length and maximum width measured by hand on every leaf, after which the sum was multiplied by 0.75, similar to procedures described by McKee (1964). The LAI ($m^2\ m^{-2}$) was calculated by dividing the summed leaf area (m^2) by the surface area of the lysimeter (0.75 m^2).

Yield Components

Aboveground dry matter and grain yield were measured by complete harvest of the lysimeter plants. Each treatment value was the mean of three 0.75 m^2 samples (three complete lysimeters). Grain was removed from the cob by hand, and grain and biomass were dried at 60°C for 5 to 7 d. Water use efficiency (WUE, in kg m^{-3}) was calculated as the ratio of either grain or aboveground biomass yield to ET in millimeters (Howell et al., 1990). Grain yield and WUE data are reported on a dry basis.

Statistical Analysis

Measurements were analyzed using general linear model procedures of SAS (SAS Inst., 1985). Treatments were randomly assigned within each pit. The model included irrigation, soil type, and the interaction. Irrigation treatment was separately tested, using the irrigation treatment within replicates error term. Mean separations were computed using the Ryan–Einot–Gabriel–Welsch multiple-range test that controls Type I experimental error or least significant differences. Covariance analysis of the relationship between grain yield and ET for each soil type and growing season was performed using procedures outlined by Freese (1964).

RESULTS AND DISCUSSION

Evaporative demand in each of the three cropping seasons was slightly different, especially from pollination through grain fill. Reference ET_o was highest in 1995, averaging 6.9 mm d^{-1} for the growing season, and 7 mm d^{-1} from anthesis through harvest (Fig. 1). Reference ET_o was lowest in 1996, averaging 5.9 mm d^{-1} for the growing season and 5.1 mm d^{-1} from anthesis through harvest. Mean growing season reference ET_o in 1994 was 6.5 mm d^{-1}, while anthesis through harvest averaged 6.3 mm d^{-1}.

Yield Components

Individual treatment (soil type and irrigation) mean separation analysis is presented in Table 3. During the 3 yr, irrigation treatments for corn in the Pullman soil produced grain yield means ranging from 389 to 804 g m^{-2} and biomass yield means from 864 to 1590 g m^{-2} with ET from 328 to 610 mm (Table 3). Mean grain yields for the corn in the Ulysses soil varied from 559 to 899 g m^{-2} and mean biomass yields from 1141 to 1648 g m^{-2} with ET from 401 to 617 mm. Mean grain

Table 4. Main effect means for irrigation treatment and for soil type of cumulative evapotranspiration (ET), grain yield, total aboveground biomass, harvest index (HI), seed number, seed mass, and grain and biomass water use efficiency (WUE) data of corn grown in lysimeter experiments at Bushland, TX (1994–1996).

Main effect	ET†	Yield		HI	Seed components		WUE§	
		Grain‡	Biomass		Seed number	Seed mass	Grain	Biomass
	mm	g m⁻²		%	no. m⁻²	mg seed⁻¹	kg m⁻³	
					1994			
Irrigation								
I-25	447b¶	656b	1207b	54a	2708b	245a	1.47a	2.70a
I-75	497a	751a	1343a	56a	3157a	238a	1.50a	2.69a
Soil type								
Pullman	425b	630b	1156b	54a	2524b	250a	1.48b	2.72a
Ulysses	533a	848a	1478a	57a	3642a	233a	1.59a	2.77a
Amarillo	457b	633b	1191b	53a	2632b	241a	1.39b	2.61a
Irrigation × Soil type	NS	NS	NS	NS	NS	NS	NS	NS
					1995			
Irrigation								
I-60	379b¶	462b	985a	47a	1989b	232a	1.22a	2.60a
I-100	403a	525a	1044a	50a	2083a	251a	1.30a	2.59a
Soil type								
Pullman	361a	411b	865b	48a	1709b	240a	1.14a	2.40a
Ulysses	420a	569a	1155a	49a	2266a	251a	1.36a	2.75a
Amarillo	392a	501ab	1023ab	49a	2134a	234a	1.28a	2.61a
Irrigation × Soil type	NS	NS	NS	NS	NS	NS	NS	NS
					1996			
Irrigation								
I-20	357d¶	563c	1093c	52a	2493b	226c	1.58a	3.06a
I-50	463c	713b	1358b	53a	2994a	239b	1.54ab	2.93ab
I-80	531b	771b	1494a	51a	2978a	259a	1.45b	2.81b
I-100	587a	796a	1555a	51a	3163a	251a	1.36c	2.65c
Soil type								
Pullman	478b	694b	1350b	51a	2797b	247a	1.45a	2.82a
Ulysses	523a	774a	1507a	51a	3146a	246a	1.48a	2.88a
Amarillo	452c	665b	1267b	53a	2779b	239a	1.47a	2.80a
Irrigation × Soil type	*	NS	NS	NS	NS	NS	NS	NS

* Significant at the 0.05 probability level.
† ET is calculated as the change in lysimeter mass between DOY 138 to DOY 242 plus any irrigation or rainfall and minus any drainage.
‡ Grain yield is reported on a dry basis.
§ Ratio of grain yield (dry basis) to ET.
¶ Main effect means followed by a different letter are significantly different within the main effect at the 0.05 probability level.

yields for the corn in the Amarillo soil ranged from 438 to 736 g m^{-2} and biomass yields from 919 to 1426 g m^{-2} with ET of 342 to 534 mm.

In each soil type, the lowest grain and biomass yields occurred in 1995 and, for ET, in the 1996 I-20 treatment. Reductions in yields in 1995 were most likely due to the higher evaporative demand during pollination and grain fill (Fig. 1). The highest grain and biomass yields and ET for the corn in the Amarillo and Pullman soils were in the 1996 I-110 treatment. The highest grain yield for the crop in the Ulysses soil, however, was in 1994, when the Ulysses soil contained about 130 mm more PAW than the Pullman soil, and about 80 mm more than the Amarillo soil.

The main effect analysis of irrigation treatment and of soil type and their interaction on yield components, WUE, and ET for the three experiments is presented in Table 4. In comparing soils, the corn in the Ulysses soil produced more than 30% more grain and 24% more total biomass in 1994 compared with the corn in the other two soils, for which yields were similar (Table 4). In 1995, the high evaporative demands during pollination and grain fill significantly reduced grain and biomass yields in the Pullman soil, compared with those in the other two soils (Table 4). Grain and biomass yields were reduced 28 and 25%, respectively, compared with the corn in the Ulysses soil, and were reduced 18 and 15%, respectively, compared with the corn in the Amarillo soil. Grain yield reductions in the crops in the Amarillo and Pullman soils were due to reduced seed numbers, which suggests that more water stress occurred in those soils prior to or during early pollination (Claassen and Shaw, 1970; Grant et al., 1989; NeSmith and Ritchie, 1992a).

In 1996, irrigation treatment comparisons showed that late-season water stress that occurred during grain fill reduced seed mass but not seed number of the crop in the I-50 treatment (Table 4) (NeSmith and Ritchie, 1992b; Eck, 1984). The corn with the I-20 treatment experienced water stress that began around silking and continued through grain fill, which significantly lowered both seed number and seed mass. The crop in the Pullman soil exhibited a more severe response to the I-20 treatment, reducing seed numbers by 22 and by 13% compared with the crops in the Ulysses and Amarillo soils, respectively (Table 3). However, at anthesis (DOY 204), the Pullman soil contained significantly higher PAW, with 117 mm remaining in the profile compared with 78 mm in both the Ulysses and Amarillo soils. NeSmith and Ritchie (1992c) observed that grain number in corn was reduced in proportion to the duration of the water-deficit period. This suggests that corn, which

Table 5. Change in leaf area index (LAI) for the 1996 I-110 irrigation treatment of corn at different growth stages at Bushland, TX (lysimeter exp.).

	LAI					
Main effect	6-leaf (171)†	8-leaf (180)	16-leaf (194)	Pollination (207)	Early grain fill (214)	Late grain fill (228)
Soil type						
Pullman	0.23a‡	0.80a	1.88a	2.05a	1.88a	1.83a
Ulysses	0.23a	0.84a	1.95a	2.08a	1.89a	1.86a
Amarillo	0.21a	0.78a	1.73b	1.82b	1.69b	1.66b

† Numbers in parentheses are Day of Year.
‡ Main effect means followed by a different letter are significantly different within the main effect at the 0.05 probability level.

slows photosynthetic rates even with minor water stress (Boyer, 1970), experienced water stress earlier in the Pullman soil than in the Ulysses or Amarillo soils, even though the Pullman soil contained more water.

The low grain yields of the corn in the Amarillo soil even under full irrigation may be due to several factors. High bulk densities and lower soil water contents have been shown to delay rooting (Bathke et al., 1992; Taylor and Gardner, 1963; Dugas et al., 1990) with a concomitant reduction in leaf area and root and shoot dry weights (Blum et al., 1977; Masle and Passioura, 1987).

Grain yield and biomass accumulation for the 3 yr produced the linear relationship of grain yield = $-61.5 + 0.57 \times$ biomass ($r^2 = 0.94$, RMSE = 36.7 g m^{-2}). The fairly stable harvest index (HI) supports Sinclair et al. (1990), who reported high linear correlations between corn grain yield and accumulated biomass, with water stress resulting in equal reductions in both biomass and yield except under severe water stress. Water stress in 1995 reduced HI by 12% compared with 1994 (Table 4), possibly due to the higher reference ET_o in 1995. DeLoughery and Crookston (1979) evaluated HI of a range of corn maturity classes and population densities in Minnesota, and determined that density and environment influenced HI more than relative maturity. The range of irrigation treatments did not significantly affect HI in 1996, possibly due to the low plant population and limited potential evaporation. Howell et al. (1995) reported that declining irrigation reduced HI of a full-season corn crop by only 11% with a population of 4.5 plant m^{-2}, but reduced HI by 41% with a population of 8.4 plant m^{-2}.

Leaf Area Development

The LAI at the end of the vegetative period was about 10% lower on the Amarillo soil compared with the crops in other two soils with the I-110 treatment in 1996, and it remained lower through grain fill (Table 5). Cumulative ET for that treatment was also 13% lower, and grain yields were 9 to 13% lower, compared with the corn in the Pullman and Ulysses soils, respectively (Table 3). The overall low LAI was in part due to plant density, as well as the reduced leaf area typical of short-season corn compared with that of full-season corn (Howell et al., 1998). Howell et al. (1998), in a study comparing ET, yield, and WUE of corn hybrids differing in maturity, reported a maximum leaf area of 4.0 with a plant density of 8.4 plants m^{-2} for the same short-season hybrid used in this study, and a maximum LAI of 5.7 for a full-season hybrid with a plant density of 8 plant m^{-2}.

Soil Water Extraction

The soil type × irrigation treatment interaction was significant only for ET in 1996 (Table 4). The interaction can be explained by the decline in soil water depletion with the lower irrigation treatments by the crops in the

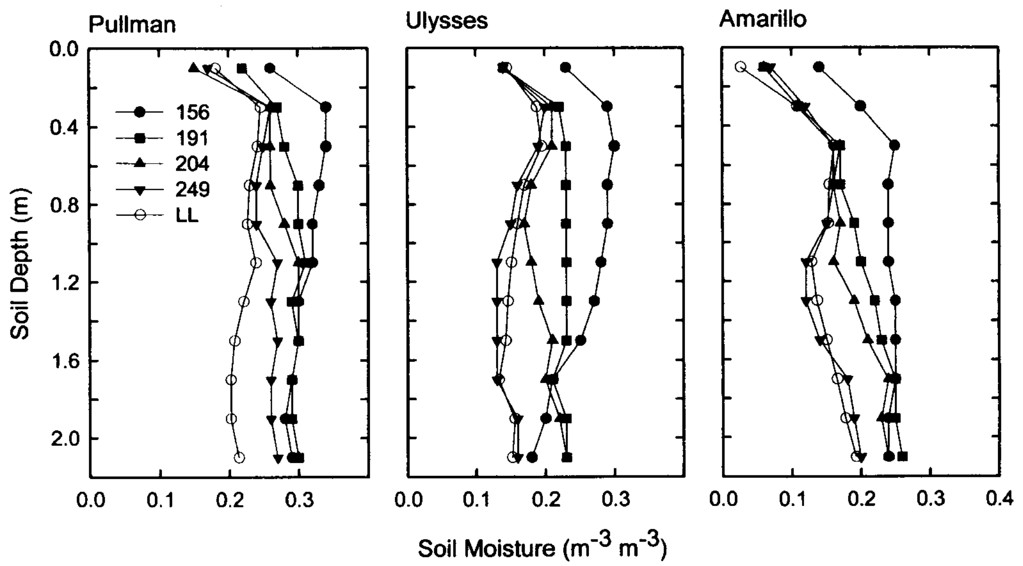

Fig. 2. Measured soil water contents for Pullman, Ulysses, and Amarillo soils for the 20% replacement of evapotranspiration irrigation treatment at corn emergence on 5 June (DOY 156), the 12-leaf growth stage on July 8 (DOY 191), anthesis on 22 July (DOY 204), and at harvest on 5 Sept. (DOY 249), along with the lower limit of water extraction by grain sorghum (LL), at Bushland, TX, in 1996.

Pullman soil compared with those in the other two soils (Table 3). In all treatments for the 3 yr, the corn in the Pullman soil extracted the least amount of soil water.

The difference in soil water extraction patterns can be seen in each soil's soil water profiles for the 1996 I-20 treatment (Fig. 2). At harvest (DOY 249), corn in the Amarillo and Ulysses soils had extracted water throughout the profile, similar to the extraction by grain sorghum, while corn in the Pullman soil left about 40 mm more water than sorghum did in the profile below 1 m, where a strong Bt horizon occurs above the calcic horizon (Table 2). (The Amarillo soil also contains a calcic horizon that begins at about 0.5 m but, in contrast to the Pullman soil, water was extracted by the crop below that depth.) This is unlike results presented by Newell and Wilhelm (1987), who reported that corn exploited deep profile water in a silty clay loam under limited to dryland irrigation, and by Stewart et al. (1975), who found that corn and sorghum extracted similar amounts of water from a deep clay loam. The Amarillo soil also contains a calcic horizon that begins at about 0.5 m, but water was extracted by the crop below that depth, unlike in the Pullman soil.

Grain Yield and Evapotranspiration Relationships

The relationship between grain yield and ET for the 3 yr is presented in Fig. 3. Neither soil type or climatic environment (year) produced significantly different slopes and intercepts, so the data were pooled, producing the linear relationship of grain yield = -45.2 g m^{-2} + 1.53 × ET (RMSE = 70 g m^{-2}, r^2 = 0.78). Other than nutrient status, soil factors are not generally considered to affect yield production based on water use (Tanner and Sinclair, 1983; Stanhill, 1986). Various linear relationships between grain yield and ET have been reported for corn, however, even for the same soil type and regional environment. Howell et al. (1995) gave the relationship as grain yield = -256 g m^{-2} + 1.70 × ET, and Musick and Dusek (1980) as grain yield = -704 g m^{-2} + 2.05 × ET, both of these for full-season corn in Pullman soil. The intercept possibly represents the soil water evaporation and crop transpiration necessary to establish some grain yield. The differences in reported slopes may be a function of mean atmospheric vapor pressure deficit (Tanner and Sinclair, 1983), difference in hybrid or maturity length, or irrigation method (Howell et al., 1995). Retta and Hanks (1980) suggested that slope differences may result from varying amounts of soil water evaporation as well.

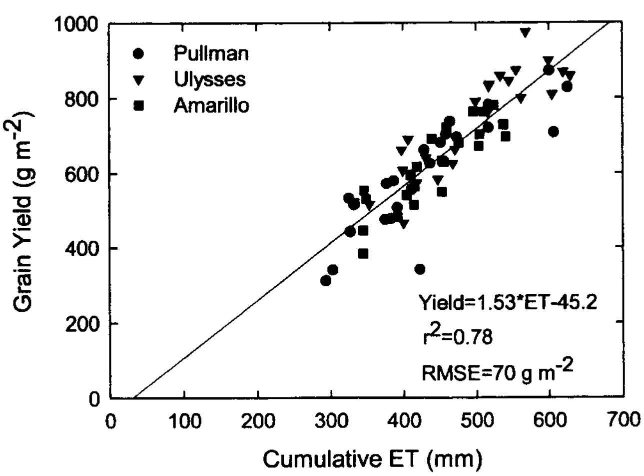

Fig. 3. Corn grain yield and cumulative evapotranspiration (ET) relationships for three cropping seasons on Pullman, Ulysses, and Amarillo soils at Bushland, TX.

Soil type did produce differences in the ranges in ET and yields. The ET and yield of the crops in the Pullman soil spanned nearly the whole range, from the lowest values (similar to those from the crops in the Amarillo soil) to near the highest (similar to the crops in the Ulysses soil) (Fig. 3). Minimum and maximum ET and yields were highest from the crops in the Ulysses soil. Maximum ET and yields were lowest from the crops in the Amarillo soil.

Grain WUE in each experiment was similar among soil types except in 1994, when the higher initial PAW in the Ulysses soil produced 25% more grain yield with only 10% more ET. Grain WUE was lowest in 1995, when limited irrigation, lower initial soil water contents, and higher reference ET_o reduced ET and yield in all treatments compared with the other two years. The decline in grain WUE with increasing irrigation in 1996 suggests that plant density limited yields and that soil water evaporation was an important component of ET in the I-80 and I-100 irrigation applications (Tanner and Sinclair, 1983).

CONCLUSIONS

Soil type did not affect the linear relationship between ET and crop grain yield. The results indicate, however, that limitations to grain yields did occur due to soil type, and these were magnified as evaporative demand increased and/or water availability declined.

In dryland production, corn planted in the Ulysses soil produced higher grain and biomass yields and used more soil water than the crops in the Pullman and Amarillo soils, because its homogeneous profile, high water storage capacity, and moderate bulk densities allowed uniform extraction with depth of all available water. The corn in the Amarillo also extracted all available water, but the amount available was limited due to textural characteristics. Corn in the Pullman soil failed to extract soil water available in the lower soil profile, possibly due to limited rooting resulting from the presence of the strong Bt horizon and possibly the calcic horizon. Musick and Dusek (1980) found that about 300 mm of water use was required to begin grain yield in the Pullman soil, which is about the maximum amount of PAW to 2.2 m that can be stored in that soil. Average precipitation of the region during the growing season for short-season corn is about 200 mm. For dryland production to be successful in both the Pullman and Amarillo soils, above-average rainfall during the growing season and a soil profile filled with water at planting would be required—which is not typical of the region.

Limited irrigation of corn could partially offset the restrictions to corn growth and yield in the Pullman and the Amarillo soils. The rapid decline in grain yields with decreases in irrigation in the Pullman soil supports the conclusions of Musick and Dusek (1980) that limited irrigation of corn should be used with caution in that soil. This is due to both the sensitivity of corn to plant water stress and the high evaporative demand of the region, which could offset the beneficial effects of moderate amounts of irrigation.

With full irrigation, corn grown in both the Pullman and Ulysses soils yielded similarly. The lower yields of corn in the Amarillo soil grown with full irrigation may have resulted from its limited water-holding capacity and some restrictions to growth due to high bulk densities, which suggests that the crop could benefit from increased irrigation frequency.

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