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Grain sorghum growth, water use, and yield in contrasting soils

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Abstract

Soil characteristics and the climate in which they occur help control crop growth and yield. We conducted a study to determine the influence of contrasting soils on grain sorghum (*Sorghum bicolor* Moench) growth, water use, and yield. In 1992 and 1993, grain sorghum ('DK-46') was grown in 0.75-m rows with 16 plants m^{-2} at Bushland, TX in lysimeters containing monolithic soil cores of silty clay loam, silt loam, and fine sandy loam. The 1992 irrigation treatments were well-watered (WW) and no applied early season irrigation to achieve a pre-anthesis water stress. The 1993 irrigation treatments were WW with limited irrigation during late vegetative and reproductive growth stages to achieve a post-anthesis water stress. The crop in the silt loam soil produced lower grain yield in 1993 under high soil water conditions, but greater grain yield, total biomass, and seed number under reduced irrigation compared with the crop on the clay loam. The crop in the sandy loam consistently produced the lowest leaf areas and yield components in all irrigation treatments, possibly due to high soil bulk densities which may have restricted rooting. The 1993 crop in the silt loam had the highest water use in all treatments, and extracted water uniformly throughout the profile in both years. High strength silty clay and clay horizons and possibly a calcic horizon in the silty clay loam may have delayed or limited rooting, and affected crop growth and yield. The crop in the sandy loam consistently produced the lowest yield components in all irrigation treatments, possibly due to restricted rooting resulting from high bulk densities and also low water holding capacity. © 1997 Elsevier Science B.V.

Keywords: Evapotranspiration; Soil strength; Clay soils; Sandy soils; Leaf area index; Lysimeter; Water use efficiency

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1. Introduction

Water management strategies, cultural practices, and crop varieties that are successful at one location may not perform as well at another due to interactions between plant, soil, and climatic factors. Plant rooting density and depth, leaf area expansion and maintenance, growth rate and stage, air temperature and humidity, and soil depth, structure, and hydraulic characteristics are all important in controlling plant water use. Ratliff et al. (1983) reported that the amount of water potentially available to plants may vary only minimally (< 3% by volume) among soil types varying widely in texture except for sandy soils, but differences in soil strength may affect rooting patterns and water extraction (Taylor and Gardner, 1963; Dwyer et al., 1988).

Water management studies in dissimilar soils under similar climatic environments are scarce. In northern Australia, total water use of rain-fed spring wheat (*Triticum aestivum* L.) in a clay loam without supplemental nitrogen was within 8% of that in a sandy clay. But, the wheat in the sandy clay had 25% more grain yield, 14% more dry matter, deeper root system, and greater total root length (Rickert et al., 1987). Pal and Varade (1982) reported higher wheat transpiration rates at lower soil water potentials in clay loam compared with sandy or sandy loam soils. They attributed these responses in the clay loam to higher plant available water contents and higher hydraulic conductivities in the range of soil water potentials encountered.

Musick and Sletten (1966) determined that grain sorghum grown in silt loam near Garden City, KS produced higher grain yields under limited irrigation (< 300 mm) than a crop in a silty clay loam at Bushland, TX. They also found that grain sorghum was greatly limited in its ability to use available soil water in the silty clay loam below 1 m where a dense B clay horizon occurs, while the crop in the less dense, more uniform silty loam depleted available soil water to about 2 m. Eck and Taylor (1969) showed at Bushland that profile modification of the clay loam by vertically mixing the profile to 1.5 m increased grain sorghum yield and water use efficiency under limited irrigation. This was due to changes in the amount and distribution of stored water and water extraction from deeper layers.

Root development and penetration into the soil profile has been found to be a function of both plant characteristics and soil properties such as soil strength (Taylor and Gardner, 1963; Taylor et al., 1966). Gerard et al. (1982) developed predictive equations for root growth in a fine sandy loam and a clay loam which included the soil factors of soil strength, bulk density, volumetric soil content, percent voids, percent clay, and soil depth. In general, they showed that cotton root growth was enhanced by moisture and voids, and retarded by increases in strength, bulk density, percent clay, and depth. A 50% reduction in maximum leaf area of grain sorghum grown in a sandy loam at Big Spring, TX compared with that in a silt loam in Garden City, KS reported by Armbrust and Bilbro (1993) may have resulted from limited rooting caused by high bulk densities of the sandy loam.

In the US southern High Plains environment, the limited and poorly distributed precipitation, declining ground water storage for irrigation, and relatively high evaporative demand require that we better understand the interrelationships between soil characteristics and crop water use so that we may maintain crop production. The objective of this research was to evaluate the growth, water use, and yield of grain sorghum grown in three different soil types typical of the southern High Plains.

2. Materials and methods

2.1. Site description

The experiment was conducted at Bushland, TX, USA, in a 0.25-ha field with a rain shelter facility that has 48 weighable lysimeters which contain three contrasting soil types. The rain shelter is a 13 m × 18 m × 3.7 m high metal building with a control sensor that automatically initiates building movement over the lysimeters when the sensor catches about 1 mm of rainfall. The lysimeters have a surface dimension of 1.0 m by 0.75 m, are 2.4-m deep, and contain monolithic soil cores with a depth of 2.3 m. A drainage system is installed in the bottom 0.1 m. They were arranged in two pits with two rows of 12 lysimeters each that are side by side in each pit. The facility and monolithic core collection techniques were described in more detail by Schneider et al. (1993).

2.2. Soil descriptions

Soil types were Pullman silty clay loam (fine, mixed thermic Torrertic Paleustoll) from Bushland, TX; Ulysses silt loam (fine-silty, mixed, mesic Aridic Haplustoll) from Garden City, KS; and Amarillo fine sandy loam (fine-loamy, mixed, thermic Aridic Paleustalf) from Big Spring, TX. These three soils are representative of the major agricultural soils in the US southern High Plains.

The soil descriptions are summarized in Table 1. The Pullman soil is characterized by a transition at about 0.18 m from a loamy A horizon of relatively low bulk density to a strong silty clay Bt horizon with higher bulk density followed by an even higher bulk density clay horizon at about 1 m. Another transition occurs along a wavy boundary at about 1.4 m to an underlying calcic B horizon with lower bulk density and up to 50% $CaCO_3$ by mass. Depth to the calcic horizon in the Pullman series can vary from about 0.5 to 1.5 m.

The Ulysses soil exhibits a fairly constant texture except for the slightly higher clay content in the B1 horizon and bulk density. Calcic material extends from the B through C horizons. The Amarillo soil exhibits a much coarser texture, higher bulk densities, and lower porosity than the other soils. Sand content is at least 54% throughout the profile. A calcic B horizon with up to 35% $CaCO_3$ occurs below about 1 m.

Textural analyses were obtained for the clay loam at the site of the core collection (personal communication, Fred Pringle, NRCS, Amarillo, TX) and in part from the county soil surveys for the sandy loam (Stoner et al., 1969) and silt loam (Harner et al., 1965). Bulk densities were measured from samples taken at each monolithic core collection site. They are the mean of at least 30 volumetric samples from each horizon. Samples were taken horizontally into an undisturbed face using a Madera probe

Table 1
Soil descriptions by horizon for the three soils. Descriptions are approximate pending laboratory analysis of samples taken at each soil core collection site

Horizon	Depth	Texture	Bulk density
	m		g cm^{-3}
Pullman silty clay loam (fine, mixed thermic Torrertic Paleustoll)			
Ap[a]	0.0 –0.18	silty clay loam	1.35
Bt1[b]	0.18–0.46	silty clay	1.44
Bt2	0.46–0.74	silty clay	1.50
Bt3	0.74–1.02	silty clay	1.47
Bt4	1.02–1.35	clay	1.55
Bk1[c]	1.35–1.98	clay loam	1.42
Bk2	1.98–2.29	clay loam	1.41
Ulysses silt loam (fine-silty, mixed, mesic Aridic Haplustoll)			
Ap	0.0 –0.13	silt loam	1.45
B1	0.15–0.28	silty clay loam	1.42
B2	0.28–0.43	silt loam	1.42
Bk	0.43–0.86	silt loam	1.38
Ck1	0.86–1.50	silt loam	1.47
Ck2	1.50–2.44	silt loam	1.35
Amarillo fine sandy loam (fine-loamy, mixed, thermic Aridic Paleustalf)			
Ap	0.0 –0.23	fine sandy loam	1.73
Bt1	0.23–0.58	sandy clay loam	1.73
Bt2	0.58–0.99	sandy clay loam	1.65
Btk	0.99–2.03	sandy clay loam	1.67

[a] p indicates plowing or other disturbance.
[b] t indicates illuvial clay (translocated silicate clay).
[c] k indicates calcic horizon.

(Precision Machine, [1] Lincoln, NE) of 60 cm^3 and oven dried at 105 C for 24 h. Samples were taken only to the 2.03 m depth in the sandy loam, but the profile below was similar to that layer. Tillage had recently been performed on the clay loam, but not on the silt loam and sandy loam prior to sampling, which may have affected the bulk densities in the surface layers.

2.3. Agronomy and irrigation

Grain sorghum (Dekalb cv. 'DK-46') was planted each year at 16 plants m^{-2} in 0.75-m row spacings with one row per lysimeter. Growth stage information is summarized in Table 2. The two irrigation treatments in 1992 were well-watered (WW) at 100% replacement of evapotranspiration (ET, in mm), and a pre-anthesis water stress treatment with no irrigation applied after the two-leaf growth stage until 11 August [Day

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

Table 2
Growth stage information

Year	Planting	Emergence	Anthesis	Harvest
1992	21 May (142)	8 June (160)	10 August (223)	5 Oct. (279)
1993	1 June (152)	12 June (163)	11 August (223)	29 Sept. (272)

Numbers in parentheses are Day of Year.

of Year (DOY) 224]. About 40 mm was applied to all treatments at planting. Irrigations were applied at three to four day intervals.

The two irrigation treatments in 1993 were WW, and post-anthesis water stress treatment. To achieve a post-anthesis stress, irrigation was reduced to 50% replacement of ET beginning on 15 July (DOY 196) during the mid-vegetative growth stage. The irrigations were applied at weekly intervals.

To insure the WW treatment received full irrigation, the WW irrigations were based on the ET of the WW silt loam crop. In a prior experiment on grain sorghum (data not shown here), the ET from the crop in the silt loam was shown to be comparable to that of the clay loam and slightly higher than that of the sandy loam.

Prior to planting, replicate soil samples from each soil type were taken to 0.25 m in the lysimeters and sent to a commercial laboratory to determine necessary fertilization requirements for optimum yield. Fertilizer application in 1992 was 14 g (N) m^{-2} for the clay loam and 15 g (N) m^{-2} for the silt loam and sandy loam. Initial fertilizer application in 1993 was 10 g (N) m^{-2} and 22 g (P) m^{-2} for the water stress irrigation treatment and 14 g (N) m^{-2} and 22 g (P) m^{-2} for the well-watered irrigation treatment on all soil types. The sandy loam received an additional 4 g (N) m^{-2} and 2 g (P) m^{-2} on 16 July (DOY 197), and all soils and treatments received 5 g (N) m^{-2} and 3 g (P) m^{-2} on 26 July (DOY 207).

A pressure-regulated drip irrigation system was used to irrigate the lysimeters and the field areas around the lysimeter pits. The flow rate of the drip emitters over the lysimeters was verified with timed, volumetric measurements.

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. No drainage occurred during the growing season in 1992 because the cores were not at field capacity. In 1993, the lysimeters were drained on 5 August (DOY 217) three weeks after the water stress treatment began with highly variable output in most cases. Average drainage and its standard deviation in the WW treatment was 47 mm (± 3 mm), 18 mm (± 15 mm), and 38 mm (± 14 mm) and in the water stress treatment was 6 mm (± 7 mm), 33 mm (± 24 mm), and 50 mm (± 28 mm) for the clay loam, silt loam, and sandy loam, respectively.

2.4. Plant growth and yield measurements

Leaf area index (LAI) was estimated from a relationship developed between measured leaf area and fraction green cover determined from overhead photographs which was similar to one described by Adams and Arkin (1977). In 1992, leaf area was measured on 1 or 2 plants per lysimeter and overhead photographs were taken. The photographs were projected onto a grid of random points and the number of points intercepted by green leaf area recorded for a fraction green cover (GC). Measured leaf area was then related to GC. The linear relationship developed was $LAI = 1.46GC + 3.15GC^2$ ($r^2 = 0.95$, RMSE = 0.55). In 1993, only overhead photographs were taken and LAI was estimated using the 1992 relationship.

Dry matter and grain yield were measured by complete harvest of the lysimeter plants. Each treatment value is a mean of three 0.75 m^2 samples. Grain was harvested using a head thresher. All grain yield data are reported at 0% water content. No grain was harvested in 1992 due to damage by birds.

2.5. Soil water measurement and use

Soil water contents were measured biweekly by neutron scattering (NS) (Model 503 DR, Campbell Pacific Nuclear, Martinez, CA) at depth increments of 0.2 m starting at the 0.1-m depth and ending at 2.1 m. Access tubes were galvanized steel electromechanical tubing. The gauge was calibrated in situ at the Garden City, KS; Big Spring, TX; and Bushland, TX 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; A, Bt, and Btk horizons of the Amarillo soil; and A and B horizons of the Ulysses soil.

ET was calculated using the water balance method. It was the difference in profile water content between the prior and current NS measurement, plus any applied water intake minus any drainage water.

2.6. Plant available water determination

Plant available water (PAW) was based on a drained upper limit (DUL) and lower limit of water extraction (LL) determined for grain sorghum by NS measurements in prior experiments (data not reported here). The data are summarized in Table 3. The prior LL study was similar to that reported herein, but extraction was based on water withdrawal by sorghum from a re-charged initial profile without any additional irrigations. The LL determined in this study was within 7% of the lower limit of extraction by multiple crops grown in silty clay loam and silt loam but 34% higher than that for the

Table 3
Water remaining in the profile to a 2.2-m depth in the three soil types for the upper limit of water extraction (DUL), lower limit of water extraction (LL), and plant available water (PAW) determined from prior experiments, as well as water remaining in the profile after water stress in 1992 and 1993

	DUL	LL	PAW	1992	1993
	mm				
Clay loam	738	482	256	481	659
Silt loam	896	348	548	319	617
Sandy loam	573	310	263	264	511

sandy loam that were reported by Ratliff et al. (1983). The higher LL for the sandy loam used in this study may be due to the higher clay contents in the deeper soil layers (Table 1). DUL was determined by NS in lysimeters which were initially filled to saturation, then sealed except for a small hole, and allowed to gravity drain until drainage stopped (about two weeks). The DUL determined in this study was similar to values reported by Ratliff et al. (1983) for silty clay loam and sandy loam, but more than 200 mm higher for the silt loam.

2.7. Micrometeorological instrumentation

Solar radiation, photon flux density, wind speed, and wet and dry bulb temperatures were measured at a nearby weather station (about 600 m) with an irrigated grass surface. Solar radiation was measured with an Eppley PSP (Eppley Laboratories, Newport, RI), photon flux density with a quantum sensor (LI-190SB, Li-Cor, Lincoln, NE), and wind speed with a cup anemometer (Model 014 A, Met One, Grants Pass, OR).

2.8. Statistical procedures

Eighteen soil cores were used in this study; the other 30 lysimeters were cropped to a different sorghum cultivar each year. To prevent irrigation treatment-related differences in microclimate and plant growth from confounding the results, the WW irrigation treatment was assigned to one pit and the water stress irrigation treatment to the other. Soil types were randomly distributed within each pit, with three replications per soil type. Measurements were analyzed using general linear model procedures of SAS (SAS Institute, 1985). 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 which controls type 1 experimental error.

3. Results

3.1. Leaf area development

Environmental conditions in 1992 and 1993 were representative of the long-term averages, except early in the season in 1992 (Table 4). Mean 2-m air temperature was lower after planting in 1992 compared with 1993 (Fig. 1) resulting in delayed emergence (Table 2) on all three soils. After the delayed emergence, the leaf development rate in the silt loam was slower compared with the other two soils, significantly reducing leaf area accumulation in the WW irrigation treatment by the 8-leaf growth stage (Table 5). The LAI of the crop in the silt loam recovered near to that in the clay loam by heading in both irrigation treatments, while LAI of the crop in the sandy loam had declined about 20 to 25% below that in the other two soil types. Significant differences in LAI between soil types were maintained through seed fill in the WW treatment, but not in the stressed treatment.

Table 4
Mean climatic summary data for sorghum growing seasons 1992 and 1993 and historical 20-year averages for Bushland, TX

	Unit	May	June	July	Aug.	Sept.	Oct.
		1992					
Maximum temp.	C	23.5	28.1	31.5	29.1	28.0	23.5
Minimum temp.	C	9.8	13.9	17.1	15.6	12.5	6.1
Dew point temp.	C	6.1	10.4	12.8	12.2	7.8	1.5
Solar radiation	MJ m^{-2} d^{-1}	20.7	24.9	25.5	21.4	20.0	14.9
Photon flux density	mol m^{-2} d^{-1}	41.5	47.0	54.5	45.1	42.3	32.0
2-m wind speed	m s^{-1}	4.1	3.7	4.5	4.3	4.6	4.1
		1993					
Maximum temp.	C	25.0	30.1	32.4	30.0	27.7	20.3
Minimum temp.	C	9.9	15.3	18.9	16.5	11.0	4.2
Dew point temp.	C	5.2	9.7	13.9	13.3	9.0	2.6
Solar rad.	MJ m^{-2} d^{-1}	23.5	24.2	24.7	21.2	19.6	14.8
Photon flux density	mol m^{-2} d^{-1}	48.7	51.0	52.2	44.8	37.8	28.3
2-m wind speed	m s^{-1}	5.1	5.4	4.9	3.5	3.7	4.1
		Historical 20-year average					
Maximum temp.	C	24.9	30.2	32.1	31.0	27.3	21.6
Minimum temp.	C	9.3	14.8	16.9	16.2	11.7	5.1
Solar radiation	MJ m^{-2} d^{-1}	24.4	26.3	25.6	22.8	19.2	15.6

In 1993, LAI at boot in the WW treatment was about 35% lower in the silt loam and the clay loam and about 10% lower in the sandy loam compared with 1992 (Table 5). Significant differences occurred in LAI after anthesis between irrigation treatments in 1993, but not between soil types, although the LAI on the sandy loam remained slightly lower throughout the season.

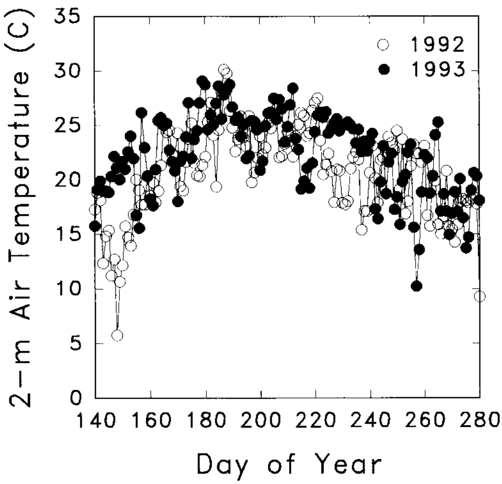

Fig. 1. The 2-m air temperature for 1992 and 1993 at an adjacent weather station.

Table 5
Leaf area index (LAI) development for 1992 and 1993 for growth stages of 8-leaf, boot, hard dough, and harvest (Harv.)

Main effect	1992				1993			
	8-leaf	Boot	Dough	Harv.	8-leaf	Boot	Dough	Harv.
	(191)[a]	(219)	(254)	(279)	(193)	(222)	(253)	(271)
Irrigation								
Well watered	1.36a[b]	4.20a	3.20a	1.85a	0.68a	2.81a	2.98a	1.17a
Water stressed	1.34a	2.68b	2.16b	1.46a	0.55a	2.56a	2.21b	0.55b
Irrigation *x* Soil	*	n.s.	*	n.s.	n.s.	n.s.	n.s.	n.s.
Well watered irrigation treatment								
Clay loam	1.59a	4.74a	4.43a	3.12a	0.82a	3.01a	3.41a	1.27a
Silt loam	0.80b	4.38a	3.36b	1.50b	0.63a	2.87a	3.05a	1.32a
Sandy loam	1.63a	3.49b	1.83c	0.93c	0.60a	2.56a	2.47a	0.92a
Water stressed irrigation treatment								
Clay loam	1.39a	2.99a	2.60a	2.18a	0.63a	2.60a	2.32a	0.63a
Silt loam	1.17a	2.86a	2.12a	1.05a	0.46a	2.91a	2.46a	0.58a
Sandy loam	1.53a	2.19a	1.77a	1.16a	0.56a	2.16a	1.86a	0.47a

[a]Numbers in parentheses are Day of Year.
[b]Main effect means followed by a different letter are significantly different within the main effect at the 0.05 probability level.
* Significant at the 0.05 level of probability.

3.2. ET and soil water depletion

Irrigation water applied during the season in 1992 was 673 mm for the WW treatment and 330 mm for the water stress treatment and, in 1993, 678 mm and 422 mm, respectively. All treatments received 33 mm rainfall in 1992, and 20 mm in 1993, usually in individual events of about 1.5 mm. The nearly identical WW irrigation application produced similar cumulative ET each year (Table 6). The water stress irrigation treatment ET was about 15% lower in 1992 compared with 1993 although it received 22% less water, possibly due to higher LAI at the beginning and end of the 1992 growing season and the different irrigation strategies.

In 1992, a significant interaction between soil type and irrigation treatment occurred (Table 6) in cumulative ET. Although the LAI of the crops in the silt loam and clay loam were similar by boot in the WW treatment (Table 5), the crop LAI in the silt loam senesced more rapidly compared with the clay loam and produced the lowest cumulative ET in that treatment. Crop LAI in the sandy loam was significantly lower by heading but did produce a cumulative ET 10% above that in the silt loam. In the water stress treatment, ET of the crops in the clay loam and silt loam were comparable. Crop LAI and water use in the sandy loam dropped below that of the other two soils by heading (data not shown), significantly reducing cumulative ET by 19% compared with the other two soils, which had comparable values.

Table 6
Crop biomass, grain yield, cumulative evapotranspiration (ET), harvest index (HI), and grain water use efficiency (WUE) data

Main effect	1992[a]		1993							
	ET	Stover[b]	ET	Stover	Grain yield[c]	Total bio.	HI	Seed #	Seed wt.	WUE
	mm	$g\ m^{-2}$	mm	$g\ m^{-2}$			%	No. m^{-2} mg	$seed^{-1}$	$kg\ m^{-3}$
Irrigation										
Well-watered	646a[d]	866a	591a	506a	514a	1342a	38a	20150a	25.3a	0.87a
Stressed	386b	491b	454b	416b	415b	1095b	38a	17400b	23.6b	0.91a
Irrigation x Soil Type	*	**	n.s.	n.s.	*	n.s.	n.s.	*	n.s.	*
Well-watered irrigation treatment										
Clay loam	688a	1036a	608a	711a	647a	1529a	42a	24760a	26.0a	1.06a
Silt loam	594a	737b	625a	751a	472b	1387a	34b	18690b	25.3a	0.76b
Sandy loam	654a	825b	540b	563a	421b	1111a	38ab	17000b	24.7a	0.78b
Stressed irrigation treatment										
Clay loam	409a	589a	476a	585b	423a	1140b	37a	17270b	24.5a	0.89ab
Silt loam	416a	495b	491a	643a	511a	1300a	39a	20710a	24.7a	1.04a
Sandy loam	334b	390c	395b	435c	309b	843c	37a	14270b	21.7a	0.79b

[a]No grain yield data were obtained.
[b]Stover is the above ground biomass minus the head mass.
[c]Grain yield is reported at 0% moisture.
[d]Main effect means followed by a different letter are significantly different within the main effect at the 0.05 probability level.
*,** Significant at the 0.05 and 0.01 probability level, respectively.

Water extraction patterns were analyzed by depth during the 1992 water stress period from 22 June to 10 August (DOY 174 to DOY 223), or from about the 3-leaf growth stage through anthesis (Table 7). At the 3-leaf growth stage, the soils had nearly equal LAI (data not shown) and the water remaining above LL was about 155 mm in the clay loam, about 160 mm in the silt loam, and about 120 mm in the sandy loam. The crops in the three soils depleted soil water in the upper 0.5 m of the profile from June to 6 July (DOY 174 to DOY 188). By 20 July (DOY 202), over 84% of water depleted by the crops in the clay loam and sandy loam was from depths < 1.2 m. Water extraction in the silt loam was fairly uniform throughout the profile. Musick and Sletten (1966) reported that grain sorghum was greatly limited in its ability to use available soil moisture below 1 m in the Pullman clay loam due to limited rooting, especially if the lower layers are only moderately wet. They also noted that a silt loam subsoil was ideal for high water storage and extensive root development. As the upper soil layers dried through 10 August (DOY 223) after which irrigation resumed, soil water depletion had extended to the lower depths similar to sunflower (Meinke et al., 1993) in both the clay loam and sandy loam.

Table 7
Soil water depletion by depth and soil type for 1992 water stress irrigation treatment

Depth (m)	Soil water depletion (mm)											
	Clay loam				Silt loam				Sandy loam			
	Ending DOY			Σ	Ending DOY			Σ	Ending DOY			Σ
	188	202	223		188	202	223		188	202	223	
0–0.4	28(15)	18(−3)	3(−6)	49	24(15)	16(−1)	6(−7)	46	36(9)	10(−1)	6(−7)	52
0.4–0.8	0(34)	24(10)	14(−4)	38	14(21)	7(14)	22(−8)	43	8(21)	22(−1)	8(−9)	38
0.8–1.2	0(27)	8(19)	22(−3)	30	0(38)	12(26)	30(−4)	42	2(28)	20(8)	18(−10)	40
1.2–1.6	0(24)	6(18)	18(0)	24	0(36)	12(24)	28(−4)	40	0(21)	8(13)	20(−7)	28
1.6–2.2	0(27)	0(27)	16(11)	16	0(16)	14(2)	6(−4)	20	0(−3)	2(−5)	4(−9)	2
Σ	28	56	73	157	38	61	92	191	46	62	36	164

Depletion represents the difference in soil water content between neutron scattering measurements made on Day of Year (DOY) 174 and DOY 188, DOY 188 and DOY 202, and DOY 202 and DOY 223.
Numbers in parentheses are amount of water remaining in the profile above grain sorghum lower limit of water extraction established in a prior experiment.

In 1993, LAI was not significantly different between soil types within each irrigation treatment (Table 5), most likely because water stress did not occur until after full leaf area development. Both sandy loam water use and leaf area development remained below those of the other two soils in both irrigation treatments throughout the season (data not shown). The water stress treatment irrigation amount was reduced 50% beginning 16 July (DOY 197) during mid-vegetative growth stage to achieve water stress during grain fill. As in 1992, most of the post-anthesis water use occurred in the upper layers in the clay loam and sandy loam, while the crop in the silt loam extracted more water from the deeper layers (Table 8). From anthesis through harvest, total ET significantly differed in all three soils in the water stress treatment, with 288 mm for the silt loam, 273 mm for the clay loam, and 245 mm for the sandy loam.

Table 8
Soil water depletion by depth and soil type in the 1993 water stress treatment

Depth (m)	Soil water depletion (mm)											
	Clay loam				Silt loam				Sandy loam			
	Ending DOY			Σ	Ending DOY			Σ	Ending DOY			Σ
	242	256	286		242	256	286		242	256	286	
0–1.6	58(137)	24(113)	20(93)	102	42(212)	22(190)	28(162)	92	46(169)	20(149)	20(129)	86
1.6–2.2	6(103)	4(99)	12(87)	22	20(134)	8(126)	18(108)	46	12(87)	0(87)	15(73)	37
Σ	64	28	32	124	62	30	46	138	58	20	35	113

Depletion represents the difference between soil water content measurements by neutron scattering made on Day of Year (DOY) 228 and DOY 242, DOY 242 and DOY 256, and DOY 256 and DOY 286.
Numbers in parentheses are grain sorghum lower limit of water extraction established in a prior experiment.

3.3. Yield

Grain yield data were not obtained for 1992 due to damage by birds. As with leaf area, the clay loam produced significantly higher stover in 1992 in both irrigation treatments compared with the other two soils. Stover yields in 1993 were highest on the silt loam in both irrigation treatments (Table 6).

A significant interaction between irrigation and soil type occurred in 1993 in grain yield, seed number, and water use efficiency (WUE) (Table 6). Yield reductions were primarily due to reduced seed number, with the highest grain yield, WUE, and seed number being produced by the clay loam in the WW treatment and by the silt loam in the water stress treatment. The sandy loam produced the lowest yield and seed number in both irrigation treatments, even though about 200 mm of water remained above PAW at the end of the season in the water stress treatment (Table 3).

4. Discussion

The similarities between the WW treatment cumulative ETs in both years in spite of large differences in leaf area support the suggestion of Ritchie (1983) that ET becomes independent of leaf area at LAIs > 2.5 when soil water is not limiting. While June was cooler in 1992 than in 1993, the bulk of leaf area development and water use occurred after that time, when both climate and water use were comparable between the 2 years.

Similar WUE between the 1993 WW and water stress irrigation treatments suggests a linear relationship between ET and grain yield (Howell, 1990; Stewart et al., 1983). Low overall WUE values also showed that a greater reduction in irrigation application would have better utilized stored water reserves, since about 200 mm remained in all three soils above LL (Table 3).

Slow early season leaf area development in 1992 by the crop in the silt loam may have been the result of early cool soil temperatures (BassiriRad et al., 1991). The high water contents in the silt loam seed zone may have limited the soil's warming capacity. All treatments received about 40 mm at planting, which was then followed by several weeks of below average temperature. The crop in the sandy loam maintained the highest LAI early in the season (data not shown) through the 8-leaf growth stage (Table 5).

The 1993 WW treatment reduced seed number of the crop in the silt loam, which suggests that early season water stress occurred (Eck and Musick, 1979). This may have been due to reduced oxygen resulting from high initial soil water contents that occurred when attempting to bring the soil to field capacity. All treatments had been saturated, allowed to drain for about two weeks, and vacuum pumped prior to planting. The soil moisture profiles at emergence for both treatments in the clay loam contained about 750 mm, the silt loam 790 mm, and the sandy loam 610 mm. The high DUL only for the silt loam suggests that some soil factor, such as structure, may be limiting drainage rate due to reduced aggregation. The Ulysses silt loam has weak soil structure throughout the profile (Harner et al., 1965). The anaerobic conditions created by excess water can affect yield even if they only occur for several days (Kramer, 1983). The reduced irrigation which began at the mid-vegetative growth stage in the water stress treatment occurred in sufficient time to not reduce silt loam yield components compared with the clay loam. The length of the waterlogging was not determined.

The lower water use and yield on the sandy loam compared with the silt loam and clay loam may have been due to the higher soil strength of the sandy loam. Factors which affect soil strength include bulk density, soil water content, and texture (Bathke et al., 1992). As soil strength increases, root penetration and proliferation decreases (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). The higher bulk densities of the sandy loam (Table 1) may have restricted root growth and limited leaf area development (Table 4). Maximum root weight in grain sorghum is reached about nine weeks after emergence (Kaigama et al., 1977) at about anthesis, by which time crop growth on the sandy loam had dropped below that on the other two soils. Yield reduction occurred even though 200 mm remained in the sandy loam profile (Table 3).

5. Conclusions

Soil type affected water use, growth, and yield of grain sorghum. The crop in the silt loam extracted water uniformly throughout the horizon. Crop yield was reduced in high soil water conditions created by poor drainage, but the highest grain yield, total biomass, and seed number were produced under more favorable soil water conditions compared with the crops in the other two soils. The tendency of the silt loam to waterlog shows what can happen in the field when both irrigation and high rainfall occur at the same time. High soil water contents may have also slowed soil heating in the cool temperatures and retarded early leaf area development.

High strength silty clay and clay horizons and possibly the calcic horizon in the clay loam may have delayed or limited rooting, and affected crop growth and yield. Profile modification of the Pullman silty clay loam by deep tillage to depths of 1.5 m have been shown to increase grain sorghum yields more than 60% compared to those from unmodified soils (Eck and Taylor, 1969), a procedure which still produced higher wheat yields 25 years later (Unger, 1993).

The crop on the sandy loam consistently produced the lowest yield components in all irrigation treatments, possibly due to high soil bulk densities which may have restricted root development and consequently leaf area and water use, as well as a lower water holding capacity. Water holding capacity might be increased by the incorporation of greater amounts of organic matter or, if the surface sandy layers are underlain by finer materials, deep tillage (Eck and Unger, 1985).

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