Lower Limits of Crop Water Use in Three Soil Textural Classes

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Accurate knowledge of the amount of soil water available for crop use allows better management of limited water supplies. Using neutron scattering, we determined the mean lower limit of field soil water use (LL_F, $m^3\ m^{-3}$) to a depth of 2.2 m at harvest (three seasons each) of short-season maize (*Zea mays* L.), grain sorghum [*Sorghum bicolor* (L.) Moench], and cotton (*Gossypium hirsutum* L.). The objective was to determine whether the laboratory-measured soil water content at -1.5 MPa matric potential ($LL_{-1.5}$, $m^3\ m^{-3}$) for each soil textural class was representative of the LL_F of each crop. The crops were grown in monolithic cores of clay loam, silt loam, or sandy loam soil contained in lysimeters with a surface dimension of 1.75 m^2 and a depth of 2.4 m at Bushland, TX. For the 2.2-m profile, the LL_F of cotton was significantly smaller than the $LL_{-1.5}$ of the silt loam soil by 0.052 $m^3\ m^{-3}$ and significantly smaller than the $LL_{-1.5}$ of the sandy loam soil by 0.016 $m^3\ m^{-3}$. The LL_F of maize was significantly larger than the $LL_{-1.5}$ of the clay loam soil by 0.037 $m^3\ m^{-3}$ and the LL_F of sorghum was significantly smaller than the $LL_{-1.5}$ of the silt loam soil by 0.045 $m^3\ m^{-3}$. Of the nine soil and crop combinations, LL_F did not vary among seasons by more than 0.01 $m^3\ m^{-3}$ in five soil and crop combinations but did vary by more than 0.01 $m^3\ m^{-3}$ in four combinations due to differences in meteorological conditions among years. Crop type, soil textural class, soil chemical layers (e.g., calcium carbonate), and interannual variations in climate all affected the ability of a crop to use soil water up to and beyond $LL_{-1.5}$.

Abbreviations: LL_F, lower limit of field water use; $LL_{-1.5}$, laboratory-measured soil water content at –1.5 MPa matric potential; PAW, plant available water.

Knowledge of the amount of soil water available for crop growth allows agricultural producers to better understand why certain crops and management strategies work best for a particular soil and environment, especially in limited irrigation and dryland crop production. This plant available water (PAW) has been defined as the volumetric water content (θ_V, $m^3\ m^{-3}$) held in a soil between an upper limit, or field capacity, and a lower limit (LL) of water content below which soil water is not available to a plant. Field capacity has been defined as the water content of the soil after having been fully wetted with water and after free drainage is negligible, and is primarily a function of soil properties. The LL has been defined as the water content that results in a plant's dormancy (incipient wilting point) or the wilting of its lower leaves and their failure to recover in a humid environment (permanent wilting point or PWP) (Cassel and Nielsen, 1986), and is a function of a combination of soil, plant, and environmental factors. Although determining LL in a field environment may be most desirable (Ritchie, 1981), the field assessment of LL (LL_F) is difficult. Substantial variation is caused by complex soil horizons and differences in rooting depths and patterns due to crop species or

Soil Sci. Soc. Am. J. 76:607–616
Posted online 3 Jan. 2012
doi:10.2136/sssaj2011.0248
Received 5 July 2011.
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crop variety, or differences by the same crop from year to year partially due to climatic demands that vary interannually.

For example, LL_F may be affected by crop factors that determine water potential gradients between soil and leaf, and soil factors that affect root density in the soil layer (Lascano and van Bavel, 1984). Passioura (1983) stated that PWP depended not only on the ultimate soil water potential to which the plant can dry the soil but also on the rate at which the roots can extract the water, both of which are affected by rooting density and differences in water content between the roots and soil. Dardanelli et al. (1997) found that rooting depth was not only a function of crop type and cultivar within a crop type but was also influenced by soil textural class and crop development.

Cabelguenne and Debaeke (1998) reported that maize and sorghum varied in LL_F values and LL_F patterns with depth in a deep silty clay loam. They found that maize extracted the most water from the top 0.5 m, but that soil water use declined rapidly at lower depths compared with the other crops. Ratliff et al. (1983) determined that crop species made only minor differences in LL_F in the upper part of the soil profile when crop rooting exceeded some critical density. Ritchie (1981) concluded that there was limited evidence of a crop type effect on LL_F and that there was little difference in extractable amounts for sorghum, maize, and cotton. An examination of 13 experiments on winter wheat (*Triticum aestivum* L.) in Australia led Angus et al. (2001) to conclude that LL_F is not unique to a soil or a soil–crop combination, but rather was influenced by the vigor of the growing crop. None of these experiments compared LL_F for the same crop grown in different soils in the same location and environment.

To simplify determination of PAW, a common laboratory procedure is to measure the water content of soil cores at matric potentials of −0.033 MPa for field capacity and −1.5 MPa for $LL_{-1.5}$ using the pressure plate technique (Cassel and Nielsen, 1986). Cabelguenne and Debaeke (1998) showed that some crops could extract soil water beyond $LL_{-1.5}$. Lehane and Staple (1960) reported LL_F of cereals measured at harvest to be 14% less than $LL_{-1.5}$. But Savage et al. (1996) concluded that $LL_{-1.5}$ corresponded to lysimetrically measured LL_F for cotton with differences between the two values of <0.01 $m^3\ m^{-3}$. Dardanelli et al. (1997) reported that maize left 0.005 $m^3\ m^{-3}$ of soil water above $LL_{-1.5}$ in a rooting depth of 1.9 m.

Soil characteristics such as texture and chemical content have been shown to affect the relationship between LL_F and $LL_{-1.5}$. Ratliff et al. (1983) found that $LL_{-1.5}$ was significantly less than LL_F for sands, silt loams, and sandy clay loams, and significantly more for loams, silty clays, and clays for a variety of crops. The presence of a calcium carbonate layer below 1.1 m limited the soil water extraction of wheat and grain sorghum from a Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustolls) (Ratliff et al., 1983).

Crop economic yields may increase if a crop can extract more water from a soil. Reported grain or cotton lint yield increases in a clay loam soil for every millimeter used after that needed for germination and stand establishment include 17.0 kg ha^{-1} for maize (Howell et al., 1995), 15.4 kg ha^{-1} for grain sorghum (Stewart et al., 1983), and 2.54 kg ha^{-1} for cotton lint (Howell et al., 2004). However, maize has had limited success as a dryland or limited irrigation crop in the southern High Plains (Musick and Dusek, 1980), unlike cotton (Howell et al., 2004) and grain sorghum (Musick et al., 1976).

The objective of this research was to compare the mean 2.2-m LL_F of three crops (cotton, maize, and grain sorghum) each paired with the mean 2.2-m laboratory-measured soil $LL_{-1.5}$ of each of three soil textural classes (clay loam, silt loam, and sandy loam) to evaluate whether $LL_{-1.5}$ is similar to LL_F. By using a rain shelter facility with lysimeters containing multiple soil textural classes in the same location, we could then remove uncertainties introduced by climatic differences at multiple locations and determine the degree to which $LL_{-1.5}$ was representative of the lower limit of water use by crops.

MATERIALS AND METHODS

Facilities

The study was conducted at the Soil-Plant-Environment Research (SPER) facility which has been in operation since 1990 at the USDA-Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, TX (35°11′ N, 102°06′ W, 1170 m elevation above mean sea level). The SPER facility had 48 lysimeters located in a uniformly cropped 0.25 ha field with a rain shelter. Design criteria for the facility included undisturbed soil profiles, sufficient soil volume and depth for normal rooting, and water potential profile (van Bavel, 1961), sufficient number of replicate treatments, and precise control of the soil water balance through rainfall exclusion and accurate irrigation applications.

The lysimeters were rectangular with a surface dimension of 1.0 m by 0.75 m and a depth of 2.4 m. Each contained a monolithic core to about the 2.3-m depth of one of the three soil series used in this study. The lysimeters were drained with a vacuum pump operating at 0.06 MPa vacuum as needed as determined by neutron moisture gauge readings. Lysimeters were arranged in two pits, with each pit containing two side-by-side rows of 12 lysimeters each.

The rain shelter was a metal building 13 by 18 m by 3.7 m high, with a control sensor that automatically initiated building movement over the lysimeters when about 1 mm of rain was detected. The facility and monolithic core collection techniques were described in more detail by Schneider et al. (1993) and Tolk et al. (2005).

Climate

The climate at Bushland is typical of the semiarid High Plains, which has a high evaporative demand of about 2600 mm yearly based on Class A pan evaporation and about 470 mm of annual precipitation. About 70% (350 mm) of the precipitation occurs from May to September when evaporative potential averages ~1520 mm. Wind direction is predominately from the south-southwest. In the predominate wind direction, there is a heterogeneous landscape of grassland and irrigated and dryland cropland.

Agronomy

Maize (Pioneer Hi-Bred International, Inc., PIO-3737[1], Johnston, IA) was grown in 1994, 1995, and 1996; grain sorghum (Pioneer Hi-Bred International, Inc., PIO-8699, Johnston, IA) in 1997, 1998, and 1999; and cotton (Delta and Pine Land Co., DP-2280, Monsanto, St. Louis, MO) in 2005, 2006, and 2007. Final plant densities for each cropping season were 4 plants m^{-2} for maize in 1994 and 1995 and 5.3 plants m^{-2} in 1996, 16 plants m^{-2} for grain sorghum, and 13.3 plants m^{-2} for cotton. The lysimeters were fertilized according to recommendations based on soil analysis before planting. Tillage was done by hand to a depth of about 0.2 m. Variability in initial soil water contents was controlled by wetting the soil profiles of all lysimeters to similar soil water depths equivalent to about 150 to 300 mm of PAW in the 2.2-m profile before planting, with amounts consistent within a project year.

Soils

The lysimeters contained monolithic soil cores of either an Amarillo fine sandy loam (fine-loamy, mixed, superactive, thermic Aridic Paleustalfs), a Pullman clay loam, or a Ulysses silt loam (fine-silty, mixed, superactive, mesic Aridic Haplustolls). Soil descriptions are given in Table 1. The Amarillo sandy loam soil is a deep, well drained, moderately permeable soil that formed in calcareous loamy materials, and has a sandy clay loam horizon below about a 0.6-m depth with increasing accumulations of calcium carbonate below a 1.1-m depth. The Pullman clay loam soil has a moderately permeable surface horizon (0–0.2 m) overlying Bt horizons with high clay contents at depths of about 0.2 to 0.7 m, and calcium carbonate horizons below a 1.3-m depth. The Ulysses silt loam soil is a very deep, well drained, moderately permeable upland soil that formed in calcareous loess, with a C horizon below about a 0.5-m depth. Based on laboratory-measured $LL_{-1.5}$ and field-measured field capacity, the Amarillo and Pullman soils have a PAW to a 2.2-m depth of about 300 mm, and the Ulysses soil a PAW of 450 mm. Textural analyses were performed by a commercial testing laboratory (Servi-Tech Laboratory, Dodge City, KS) using samples taken at the lysimeter collection site.

Table 1. Soil descriptions by horizon for the three soil series.

Horizon†	Depth	Texture‡	Sand	Silt	Clay	Bulk density
	m		%			Mg m^{-3}
Amarillo series (fine-loamy, mixed, superactive, thermic Aridic Haplustolls)						
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	1.72
Bt1	0.58–0.84	scl	58.0	15.3	26.7	1.65
Bt2	0.84–1.19	scl	63.9	13.7	22.4	1.66
Btk1	1.19–1.40	scl	53.7	19.3	27.0	1.66
Btk2	1.40–1.73	scl	55.2	18.4	26.4	1.69
Btk3	1.73–2.03	scl	51.8	22.0	26.2	1.71
Btk4	2.03–2.20	cl	40.9	31.4	27.7	1.71
Pullman series (fine, mixed, superactive, thermic Torrertic Paleustolls)						
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	1.98–2.20	sicl	19.5	44.0	36.5	1.41
Ulysses series (fine-silty, mixed, superactive, mesic Aridic Haplustolls)						
Ap	0.0–0.13	sl	21.9	53.1	25.0	1.45
A	0.13–0.25	sl	21.9	51.2	26.9	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

† 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.

‡ Texture: c is clay, l is loam, s is sand, si is silt.

Lower Limit of Water Availability

Field Determination

The LL_F for each crop and soil combination was determined from volumetric soil water contents measured using a neutron moisture gauge (Model 503 DR1.5, Campbell Pacific Nuclear, Inc., Concord, CA) in a centrally located vertical access tube in each lysimeter. The gauge measurements were taken at 0.2-m increments starting at 0.1-m depth and ending at 2.1-m depth. 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) and Evett (2008). During calibration, about 24 volumetric soil samples were obtained for each 0.2-m thick soil layer, beginning at 0.1-m depth and sampling at 0.2-m increments below that to at least the 1.9-m depth. Samples were taken horizontally into an undisturbed face using a Madera probe (Precision Machine, Lincoln, NE) of 60 cm^3 and oven dried at 105°C for 24 h. The samples were of known volume (60 cm^3) so θ_v was calculated by dividing the volume of water removed by drying (determined from the mass of water lost on drying and the density of water) by the sample volume. Depth of soil water (mm) was calculated by multiplying θ_V by the soil depth (mm). The soil bulk density was calculated by dividing the mass of dry soil by the sample volume, and the mean bulk densities for each soil layer were calculated from the layer soil bulk density values (about 24 for each 0.2-m layer).

Separate calibration equations were developed for each major soil horizon. The gauge calibration statistics for each layer of each soil are given in Evett (2000). The standard error of estimate for these calibrations was always <0.01 m^3 m^{-3}. Each spring, the stability of meter calibrations was ensured by cross-

[1] The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture. USDA is an equal opportunity provider and employer.

calibration against standards consisting of 208-L drums filled with water and sand, and against wax-filled standards (Troxler Laboratories, Raleigh, NC) representing three equivalent moisture contents using methods similar to those reported by Hodnett and Bell (1991) and Reginato and Nakayama (1988). Beginning in 1999, cross-calibrations were performed in the field using access tubes in relatively wet and dry soil sites.

Using θ_v values determined by gauge, the mean soil water content for the 2.2-m profile was used to determine LL_F values for the soils and crops to a depth of 2.2 m in each lysimeter. Given the standard error of estimate was <0.01 $m^3\ m^{-3}$, θ_v was reported in three significant digits.

It is important to note that in each cropping season, the 48 lysimeters were being used in other irrigation experiments that involved a range in irrigation application amounts based on experimental objectives. The data used in the present comparison among crops within soil textural class were taken from lysimeters where the crop had little to no early season water stress which allowed the crop and rooting system to fully develop. The rain shelter allowed control of the soil water balance for the development of mid- and late-season water stress which was essential so that root water uptake could fully dry the soil to the lower limit of extraction. Changes in soil water content were monitored throughout the season. Soil profile water content measurements taken at harvest were considered to be representative of the maximum drying potential (Cabelguenne and Debaeke, 1998; Lehane and Staple, 1960). The data from lysimeters used in this analysis were primarily from deficit irrigation treatments (not fully meeting crop water needs) because lysimeters irrigated to fully meet crop water needs often had stored soil water at harvest. The lysimeters received irrigation ranging from 150 to 300 mm during vegetative development plus additional irrigation ranging from 0 to 600 mm based on irrigation strategy, soil water content, and seasonal water requirements (irrigation amount based on replacement of evapotranspiration [ET] and fractions thereof to develop soil water deficits). The largest standard deviation among replicates (lysimeters) in a soil and crop combination used in the analyses was 0.015 $m^3\ m^{-3}$ but was often <0.01 $m^3\ m^{-3}$ (Table 2). Possible errors in this approach include changes in water content not due to crop water use, such as upward capillary flow, drying of upper soil layers, and drainage; random instrument errors; and limited rooting especially at depths below 1.5 m. Data for the 0.1-m depth, where evaporative drying reduced the soil water content below that which could be extracted by the crop, were obtained from $LL_{-1.5}$ determined in the laboratory. The number of replicates used in the analyses is shown in Table 2.

Laboratory Determination

The $LL_{-1.5}$ values were determined using the pressure plate technique following procedures described by Klute (1986). All samples used in the analysis came from larger bulk samples of each soil layer collected at each soil series collection site. Four subsamples from each soil layer were sieved through a 0.002-m screen, placed in 0.05-m diam. by 0.015-m tall rings with lead weights on the top, saturated, and allowed to equilibrate at −1.5 MPa pressure for about 9 d. The subsamples were oven dried at 105°C for 24 h. Mass-basis water content (kg kg^{-1}) was converted to θ_v by multiplying by the bulk density of the soil layer corresponding to each sample.

Error can be introduced into this procedure due to differences in water retention by sieved samples as compared with undisturbed core samples. Unger (1975) compared water retention at −1.5 MPa between sieved and undisturbed core samples ranging in texture from sand to clay. He found that at −1.5 MPa, core samples contained about 1% more water than sieved soils. Elrick and Tanner (1955) concluded that the moisture retention of sieved samples can represent that of undisturbed core samples of medium textured soils within a relative error of 10%, with water contents of sieved samples at −1.5 MPa being smaller than those of core samples. The latter authors noted that differences in equilibrium criteria may have accounted for the smaller water contents in sieved soils. Core samples are typically taller than sieved samples in rings and core samples may more easily lose contact with the pressure plate at −1.5 MPa pressure.

Table 2. The field measured lower limit of water use (LL_F) to a 2.2-m depth by soil textural class, crop, and year with number of replicates (lysimeters) and laboratory-measured soil water content measured at −1.5 MPa using the pressure plate technique ($LL_{-1.5}$). Data are arithmetic mean ± 1 standard deviation.

Lower limits	Year	Amarillo sandy loam		Pullman clay loam		Ulysses silt loam	
		$m^3\ m^{-3}$	no.	$m^3\ m^{-3}$	no.	$m^3\ m^{-3}$	no.
$LL_{-1.5}$		0.129 (±0.009)	4	0.199 (±0.014)	4	0.176 (±0.006)	4
Cotton LL_F							
	2005	0.112 (±0.003)	5	0.206 (±0.004)	8	0.123 (±0.002)	6
	2006	0.128 (±0.014)	5	0.204 (±0.003)	8	0.127 (±0.003)	7
	2007	0.100 (±0.004)	6	0.200 (±0.004)	7	0.121 (±0.002)	6
	Avg.	0.113 (± 0.014)	16	0.204 (±0.004)	23	0.124 (± 0.004)	19
Maize LL_F							
	1994	0.140 (±0.006)	5	0.237 (±0.002)	5	0.176 (±0.008)	8
	1995	0.137 (±0.008)	6	0.232 (±0.013)	4	0.154 (±0.004)	9
	1996	0.136 (±0.004)	3	0.241 (±0.002)	3	0.147 (±0.003)	3
	Avg.	0.138 (±0.006)	14	0.236 (±0.008)	12	0.162 (±0.014)	20
Grain sorghum LL_F							
	1997	0.124 (±0.015)	6	0.224 (±0.004)	6	0.136 (±0.007)	6
	1998	0.119 (±0.008)	6	0.225 (±0.012)	6	0.132 (±0.002)	5
	1999	0.110 (±0.005)	6	0.197 (±0.007)	6	0.125 (±0.002)	6
	Avg.	0.118 (±0.011)	18	0.215 (±0.015)	18	0.131 (±0.006)	17

Data Analysis

A generalized linear mixed model (PROC GLIMMIX, SAS version 9.2, SAS Institute, Cary, NC) was used to compare $LL_{-1.5}$ (control) to LL_F (response variable) determined from the 3 yr and the multiple measurement depths of the 2.2-m

profile for each crop and soil combination. This model allows for the analyses of unbalanced data (multiple missing values) with random effects such as years (McCulloch and Neuhaus, 2005). Since the 2.2-m LL_F and $LL_{-1.5}$ profiles were measured at different depth increments (see Table 1 for $LL_{-1.5}$ depths), the repeated depth measurement (across cropping seasons for each crop and across replicates for $LL_{-1.5}$) was modeled using a spatial exponential covariance structure. The crop and soil were both considered fixed effects and a Dunnett's two-sided comparison for unbalanced data was calculated using the LSMEANS option. Degrees of freedom were calculated using the Kenward–Roger method to account for unbalanced data. This comparison against $LL_{-1.5}$ within each crop and soil combination achieved a more powerful and directed statistical test.

RESULTS

LL_F vs. $LL_{-1.5}$

For a 2.2-m profile in the Amarillo sandy loam soil, the LL_F of cotton was 0.113 $m^3\ m^{-3}$ which was significantly lower (p = 0.02, based on least squares means) by 0.016 $m^3\ m^{-3}$ than the $LL_{-1.5}$ (0.129 $m^3\ m^{-3}$) of that soil (Fig. 1, Tables 2 and 3). The LL_F of maize (0.138 $m^3\ m^{-3}$) and grain sorghum (0.118 $m^3\ m^{-3}$) were similar to the sandy loam $LL_{-1.5}$ of the sandy loam. While the LL_F of maize tended to be similar to $LL_{-1.5}$ to a depth of 1.6 m, the cumulative differences, especially those below 1.6 m, resulted in a difference between $LL_{-1.5}$ and LL_F for the total 2.2-m profile that resulted in a difference level of p = 0.09 (Table 3).

The LL_F of maize (0.236 $m^3\ m^{-3}$) in the Pullman clay loam soil was significantly larger (p = 0.0003) than the $LL_{-1.5}$ (0.199 $m^3\ m^{-3}$) of that soil by 0.037 $m^3\ m^{-3}$ (Fig. 2, Tables 2 and 3). The LL_F of cotton (0.204 $m^3\ m^{-3}$) and grain sorghum (0.215 $m^3\ m^{-3}$) were similar to the clay loam $LL_{-1.5}$. For the three crops, $LL_{-1.5}$ tended to be less than LL_F below 1.6 m in that soil.

In the Ulysses silt loam soil, the LL_F of cotton (0.124 $m^3\ m^{-3}$) was significantly lower (p < 0.0001) than the silt loam $LL_{-1.5}$ (0.176 $m^3\ m^{-3}$) by 0.052 $m^3\ m^{-3}$ and the LL_F of grain sorghum (0.131 $m^3\ m^{-3}$) was significantly lower (p < 0.0001) than $LL_{-1.5}$ by 0.045 $m^3\ m^{-3}$ (Fig. 3, Tables 2 and 3). The LL_F of maize (0.162 $m^3\ m^{-3}$) was similar to the silt loam $LL_{-1.5}$ with variability increasing below about 1.2 m.

Cropping Season Comparisons

Of the nine soil and crop combinations (e.g., Fig. 1–3), LL_F did not vary among years by more than 0.01 $m^3\ m^{-3}$ in five soil and crop combinations but did vary by more than 0.01 $m^3\ m^{-3}$ in four combinations (Table 2). Of the combinations which did vary more than 0.01 $m^3\ m^{-3}$, mean LL_F of cotton was 0.112 $m^3\ m^{-3}$ in 2005 and 0.10 $m^3\ m^{-3}$ in 2007 but was 0.128 $m^3\ m^{-3}$ in 2006 in the Amarillo sandy loam soil (Fig. 4). The LL_F of grain sorghum in the Pullman clay loam soil was almost identical in 1997 and 1998 (0.224 $m^3\ m^{-3}$ and 0.225 $m^3\ m^{-3}$, respectively) but, in 1999, the LL_F was 0.197 $m^3\ m^{-3}$ (Fig. 4). The LL_F of maize in the Ulysses silt loam soil was 0.176 $m^3\ m^{-3}$ in 1994, 0.154 $m^3\ m^{-3}$ in 1995, and 0.147 $m^3\ m^{-3}$ in 1996, with the difference in 1994 from 1995 and 1996 being reduced soil water use below about 1.2 m (Fig. 4). The LL_F of grain sorghum was progressively smaller in the Amarillo sandy loam soil, declining an average of 0.014 $m^3\ m^{-3}$ from 1997 to 1999 (Table 2). Crop and soil combinations that varied <0.01 $m^3\ m^{-3}$ among the 3 yr for the 2.2-m profile included maize in the Amarillo sandy loam and Pullman clay loam soils, cotton in the Pullman clay loam and Ulysses silt loam soils, and grain sorghum in the Ulysses silt loam soil.

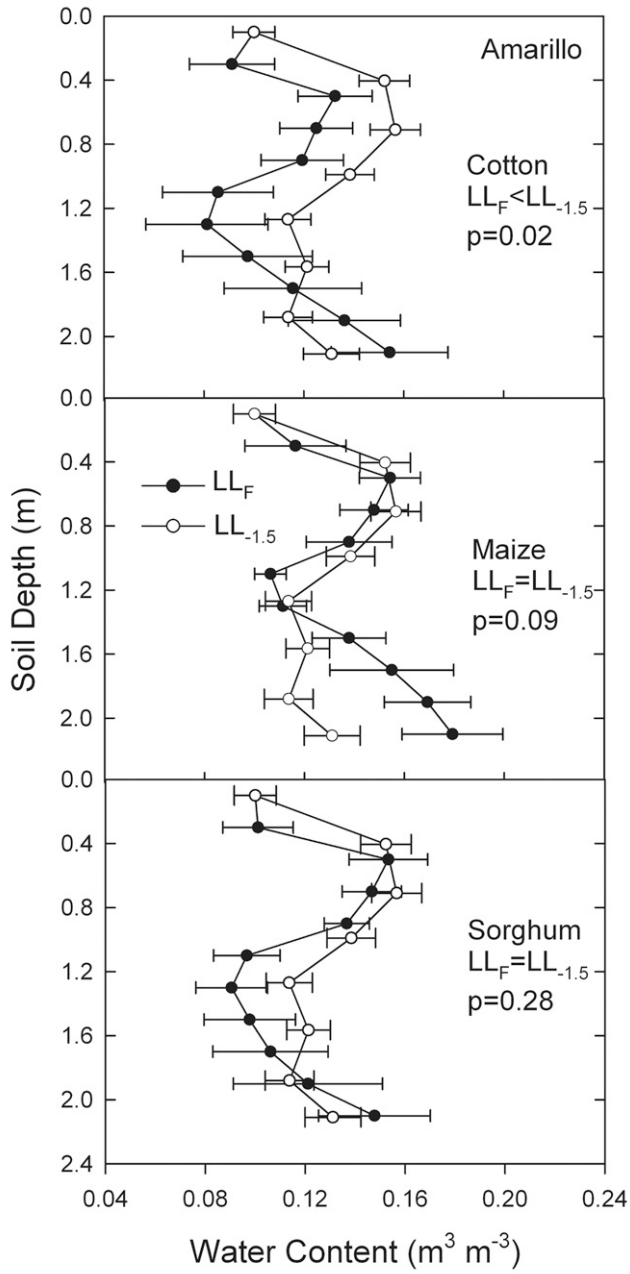

Fig. 1. The 3-yr average lower limit of water use (LL_F, $m^3\ m^{-3}$) for cotton, maize, and grain sorghum grown in the Amarillo sandy loam soil and the soil's laboratory-measured water content at -1.5 MPa matric potential ($LL_{-1.5}$). Horizontal lines are ± 1 standard deviations of the number of n replicate lysimeters for each measurement depth of 0.2 m.

Crop Comparisons within Soils

The LL_F of the three crops showed similar changes in water content as soil texture changed through the profile in each soil

Table 3. Statistical analyses results using PROC GLIMMIX comparing the field-measured lower limit of water use (LL_F, $m^3\ m^{-3}$) and laboratory-measured soil water content measured at -1.5 MPa using the pressure plate technique ($LL_{-1.5}$, $m^3\ m^{-3}$) by soil textural class (Amarillo sandy loam, Pullman clay loam, Ulysses silt loam) and crop (cotton, maize, grain sorghum). Parameters include the difference of the estimated least squares means difference (LS diff) and the standard error of the LS means (SE).

Parameters	Amarillo LL_F vs. $LL_{-1.5}$			Pullman LL_F vs. $LL_{-1.5}$			Ulysses LL_F vs. $LL_{-1.5}$		
	Cotton	Maize	Sorghum	Cotton	Maize	Sorghum	Cotton	Maize	Sorghum
LS difference, $m^3\ m^{-3}$	–0.018	0.0143	–0.0113	–0.0001	0.04	0.013	–0.055	–0.013	–0.0483
SE, $m^3\ m^{-3}$	0.0072	0.0080	0.0101	0.0063	0.0081	0.0086	0.0052	0.0079	0.0061
t value	–2.52	1.80	–1.11	–0.02	4.93	1.51	–10.57	–1.65	–7.9
p	0.02	0.09	0.28	0.99	0.0003	0.14	<0.0001	0.11	<0.0001

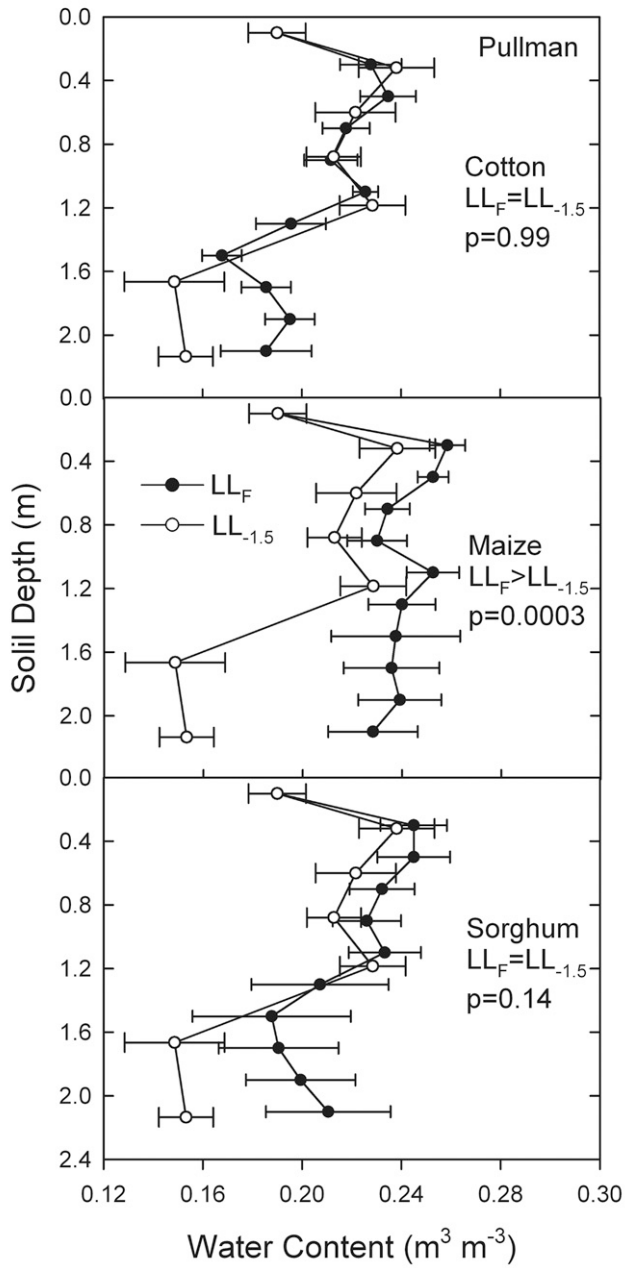

Fig. 2. The 3-yr average lower limit of water use (LL_F, $m^3\ m^{-3}$) for cotton, maize, and grain sorghum grown in the Pullman clay loam soil and the soil's laboratory-measured water content at –1.5 MPa matric potential ($LL_{-1.5}$). Horizontal lines are ±1 standard deviations of the number of n replicate lysimeters for each measurement depth of 0.2 m.

textural class (Fig. 5). But, the amount of water held at LL_F by each crop, and the relationship between LL_F and $LL_{-1.5}$, tended to differ among crops and the relationship changed with profile depth.

Amarillo Sandy Loam

For the 2.2-m profile of the Amarillo sandy loam soil, the LL_F of grain sorghum was an average of 0.02 $m^3\ m^{-3}$ and cotton an average of 0.025 $m^3\ m^{-3}$ smaller than the LL_F of maize (Table 2). But, from the surface to 1.2 m, the LL_F of maize and grain sorghum were similar while the LL_F of cotton was 0.02 $m^3\ m^{-3}$ smaller (Fig. 5). All three crops tended to use more water to a 1.2- m depth than that held at $LL_{-1.5}$ with the difference between soil $LL_{-1.5}$ and crop LL_F ($LL_{-1.5}$-LL_F) being about 0.03 $m^3\ m^{-3}$ for cotton, 0.01 $m^3\ m^{-3}$ for maize, and 0.02 $m^3\ m^{-3}$ for grain sorghum. Below 1.2 m in the soil's calcium carbonate layer (Table 1), the LL_F of grain sorghum averaged 0.04 $m^3\ m^{-3}$ and of cotton averaged 0.03 $m^3\ m^{-3}$ less compared with that of maize. Maize LL_F was about 0.04 $m^3\ m^{-3}$ larger than $LL_{-1.5}$ while the LL_F of cotton and grain sorghum was not larger than $LL_{-1.5}$ until below 1.6 m.

Pullman Clay Loam

In the 2.2-m Pullman clay loam soil profile, the average LL_F of grain sorghum was 0.021 $m^3\ m^{-3}$ smaller and the average LL_F of cotton was 0.032 $m^3\ m^{-3}$ smaller than the average LL_F of maize (Table 2). The cotton and grain sorghum LL_F differed only by about 0.01 $m^3\ m^{-3}$ in the 2.2-m soil profile, and both were within 0.01 $m^3\ m^{-3}$ of $LL_{-1.5}$ to the 1.6-m depth (Fig. 5). Maize LL_F was 0.02 $m^3\ m^{-3}$ larger than cotton LL_F and 0.01 $m^3\ m^{-3}$ larger than grain sorghum LL_F to a depth of 1.2 m. Below 1.6 m in the soil's calcium carbonate layer (Table 1), LL_F of cotton was 0.039 $m^3\ m^{-3}$ and the LL_F of grain sorghum was 0.05 $m^3\ m^{-3}$ larger than $LL_{-1.5}$. From 1.2 to 2.2 m, the difference between the LL_F of maize and cotton increased to 0.05 $m^3\ m^{-3}$ and between the LL_F of maize and grain sorghum increased to 0.04 $m^3\ m^{-3}$.

Ulysses Silt Loam

In the 2.2-m Ulysses silt loam soil profile, grain sorghum LL_F tended to have an average of about 0.03 $m^3\ m^{-3}$ and cotton LL_F 0.04 $m^3\ m^{-3}$ more water than maize LL_F (Table 2). For the 1.8-m soil profile (Fig. 5), the LL_F of cotton had 0.035 $m^3\ m^{-3}$ less water and the LL_F of grain sorghum had 0.023 $m^3\ m^{-3}$ less water than that held at $LL_{-1.5}$ while the LL_F of maize (0.162 $m^3\ m^{-3}$) was similar to $LL_{-1.5}$ (0.16 $m^3\ m^{-3}$). The LL_F of maize became

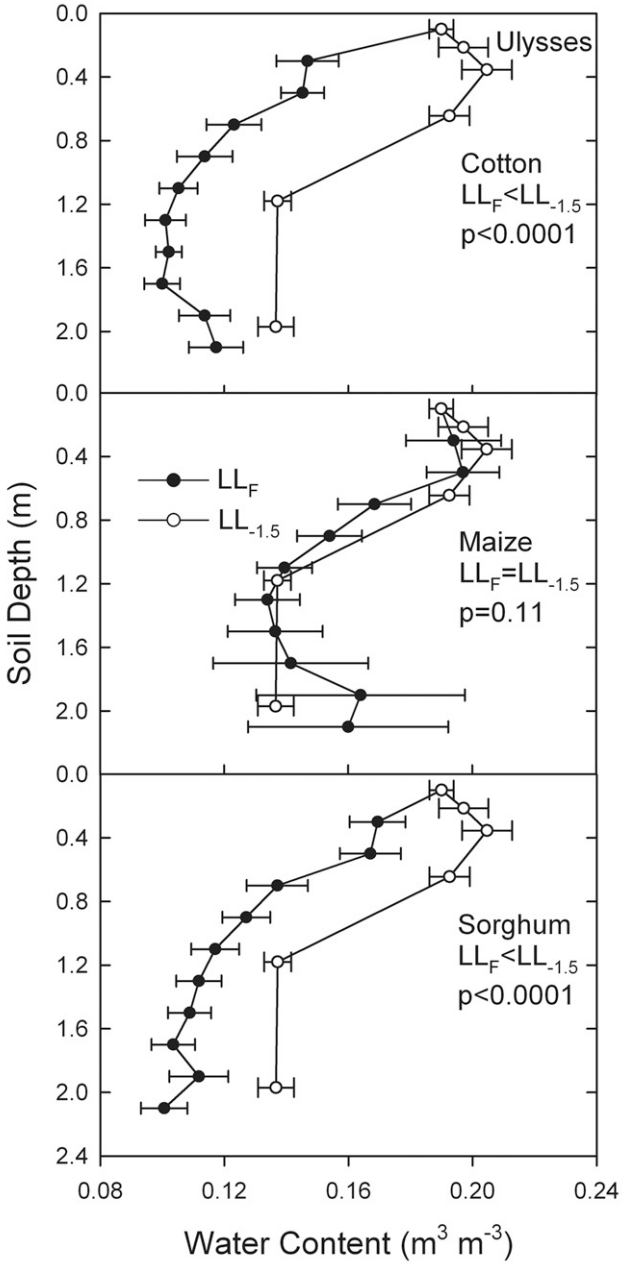

Fig. 3. The 3-yr average lower limit of water use (LL_F, m^3 m^{-3}) for cotton, maize, and grain sorghum grown in the Ulysses silt loam soil and the soil's laboratory-measured water content at –1.5 MPa matric potential ($LL_{-1.5}$). Horizontal lines are ± 1 standard deviations of the number of n replicate lysimeters for each measurement depth of 0.2 m.

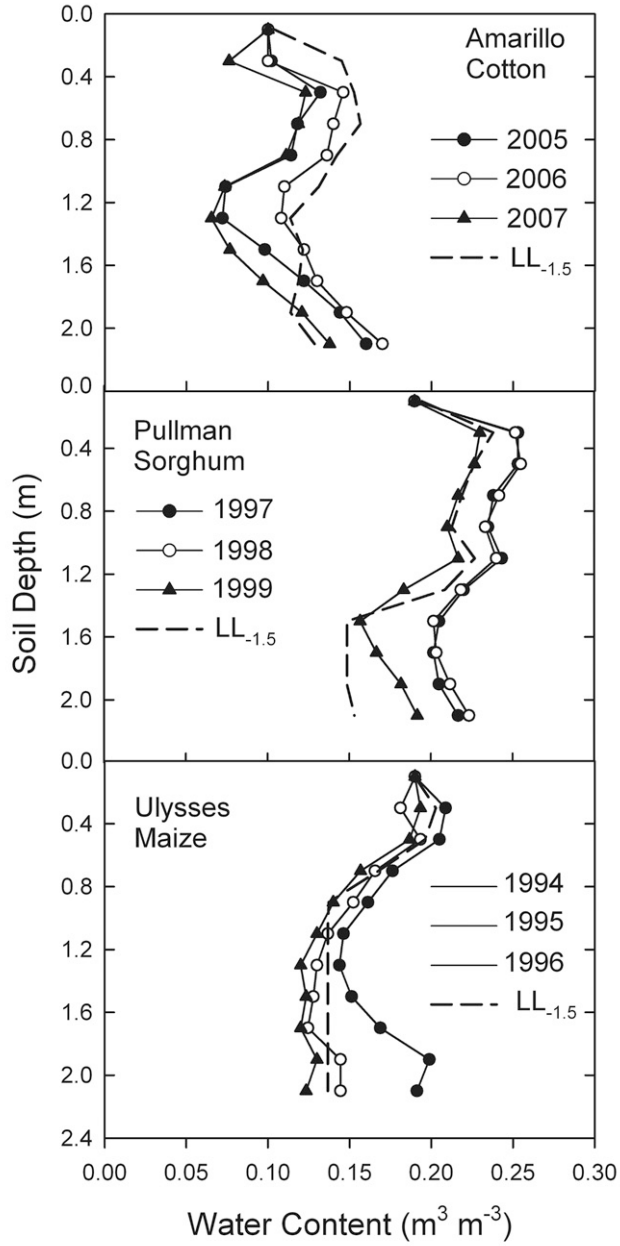

Fig. 4. The lower limit of water use (LL_F, m^3 m^{-3}) for each cropping year of cotton in the Amarillo sandy loam soil, grain sorghum in the Pullman clay loam soil, and maize in the Ulysses silt loam soil, and the laboratory-measured water content at –1.5 MPa matric potential ($LL_{-1.5}$) for each soil.

increasingly variable with depth below 1.6 m because of the reduced water use in 1996 compared with 1994 and 1995 (Fig. 4).

DISCUSSION

Ratliff et al. (1983) determined that $LL_{-1.5}$ was significantly less than LL_F for sands, silt loams, and sandy clay loams and significantly more than LL_F for loams, silty clays, and clays. In the current study, the relationship of LL_F to $LL_{-1.5}$ was not consistent among crops within each soil textural class. The LL_F of cotton was significantly smaller than $LL_{-1.5}$ and the LL_F of grain sorghum and maize were similar to $LL_{-1.5}$ in the Amarillo sandy loam. The LL_F of maize was significantly larger than $LL_{-1.5}$ and the LL_F of grain sorghum and cotton were similar to $LL_{-1.5}$ in the Pullman clay loam soil. In the Ulysses silt loam, the LL_F of cotton and grain sorghum were significantly smaller than $LL_{-1.5}$ while the LL_F of maize was similar to $LL_{-1.5}$. However, the crops did respond similarly to changes in soil textural classes, with the crop LL_F tending to decrease in relation to $LL_{-1.5}$ in the order of clay loam, sandy loam, and silt loam. The ratios of average LL_F to average $LL_{-1.5}$ for the 2.2-m profile were 1.03, 0.88, and 0.70 for cotton; the ratios were 1.19, 1.07, and 0.92 for maize; and the ratios were 1.08, 0.91, and 0.74 for grain sorghum; for clay loam, sandy loam, and silt loam, respectively.

Ratliff et al. (1983) also concluded that crop species made only minor differences in LL_F in the upper part of the profile

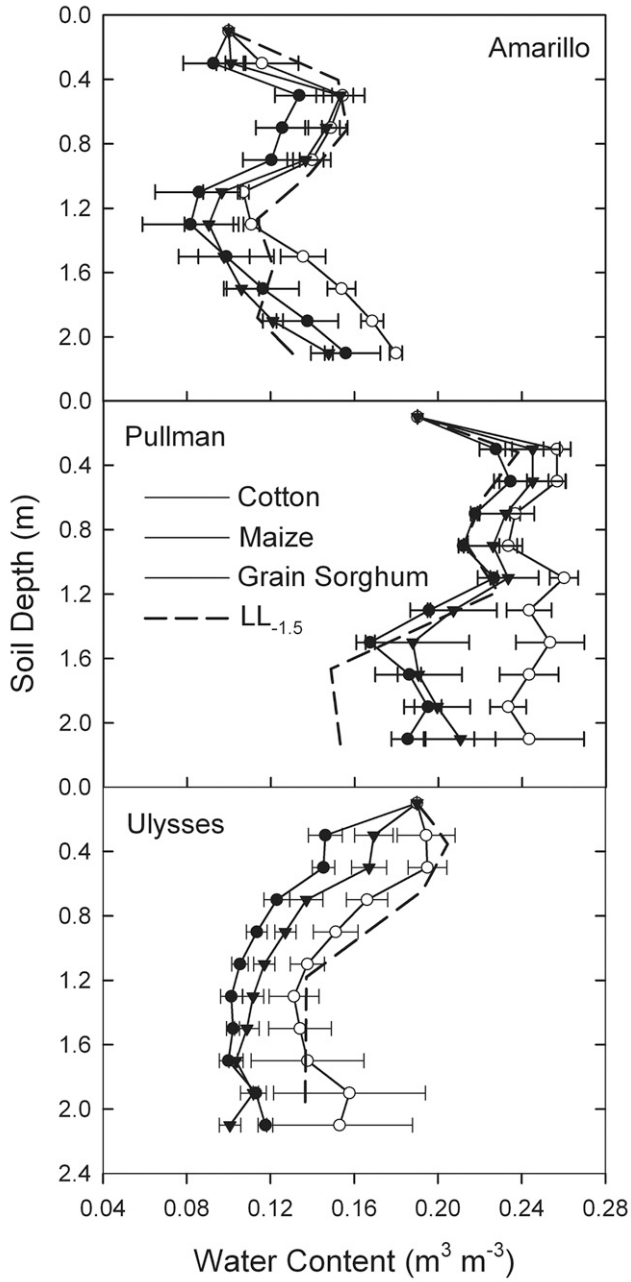

Fig. 5. The 3-yr average lower limit of water use (LL_F, $m^3\ m^{-3}$) for cotton, maize, and grain sorghum grown in the Amarillo sandy loam, Pullman clay loam, and Ulysses silt loam soils and the laboratory-measured water content at –1.5 MPa matric potential ($LL_{-1.5}$) for each soil. Horizontal lines are ± 1 standard deviations of the number of n replicates for each measurement depth of 0.2 m.

because rooting length density was above some critical value. While they could not be compared statistically for differences, the LL_F to a 1.2-m depth in the Amarillo sandy loam soil was 0.109 0.127, and 0.122 $m^3\ m^{-3}$ for cotton, maize, and grain sorghum, respectively (Fig. 5). The LL_F to a 1.2 m depth in the Pullman clay loam soil was 0.218, 0.236, and 0.227 $m^3\ m^{-3}$ for cotton, maize, and grain sorghum, respectively. The LL_F to a 1.2-m depth in the Ulysses silt loam soil was 0.137, 0.174, and 0.152 $m^3\ m^{-3}$ for cotton, maize, and grain sorghum, respectively. Both Cabelguenne and Debaeke (1998) and Hattendorf et al. (1988) reported differences in the amount of water crops extracted with soil depth. Cabelguenne and Debaeke (1998) found that maize had the greatest soil water extraction to a 0.6-m depth compared with grain sorghum in a silty clay alluvial soil. Hattendorf et al. (1988) also reported extraction by maize from the top 1 m soil profile to be 35 to 50% greater than that by grain sorghum in silt loam soils.

Dardanelli et al. (1997) and Cabelguenne and Debaeke (1998) reported rapid declines in water use by maize below about 1.5 m as was observed in this study (Fig. 5). Cabelguenne and Debaeke (1998) found that water use by sorghum continued to depths below 1.6 m, as was suggested by $LL_F < LL_{-1.5}$ for both grain sorghum and cotton as compared with maize in the Ulysses soil (Fig. 5). When comparing root systems of maize, sorghum, and soybean [*Glycine max* (L.) Merr.], Mayaki et al. (1976) found that only maize had no roots below a 1.5-m soil depth. Nielsen et al. (2011) used different LL_F values for four different groups of crop species, with sunflower (*Helianthus annuus* L.) showing much lower LL_F than other species in the 0.9 to 1.8 m portion of the soil profile.

The differences in the amount of water remaining in the profile also suggest that cotton and grain sorghum may regulate water use differently than maize. Ackerson and Krieg (1977) compared the stomatal and nonstomatal regulation of water use in cotton, maize, and sorghum and found that both cotton and sorghum had variable internal resistances that regulated water flux through the plant under different soil water conditions. Maize did not have a variable internal resistance to water flux such that, even if soil water was readily available, it reached water stress levels rapidly under conditions of high evaporative demand, which resulted in reduced water use. Kang et al. (2000) reported reduced stomatal conductance by maize in hot and dry weather and in soil with high soil moisture contents.

Season length may also have limited water use by maize. The maize hybrid used was in a short season maturity class with a relative maturity length of 105 d. Howell et al. (1998) showed that 0.04 $m^3\ m^{-3}$ more water was used in the 0.5- to 1.5-m soil profile depth for a full season maize hybrid (115 d relative maturity length) compared with short season maize hybrid grown with the same irrigation regime.

The presence of well-developed calcium carbonate layers in the lower part of the soil profiles of the Pullman clay loam and Amarillo sandy loam soils may also have affected water use from those depths. Below 1.4 m in the Ulysses soil, the LL_F of grain sorghum and cotton tended to contain about 20% less water than that held at $LL_{-1.5}$. But below 1.4 m in the Pullman soil, the LL_F of the two crops tended to contain more water than the amounts held at $LL_{-1.5}$, which suggests reduced rooting in the calcium carbonate layer. Moroke et al. (2005) reported root length densities of grain sorghum of less than 1.0 $m^3\ m^{-3}$ at a 1.5-m depth in the Pullman clay loam compared with root length densities of about 3.0 $m^3\ m^{-3}$ in the upper 0.5 m soil profile. The LL_F of the three crops also increased with depth below 1.1 m compared to $LL_{-1.5}$ in the Amarillo sandy loam profile.

Differences in LL_F among years within a crop species may be due to an interaction between interannual variations in climate and soil textural class. High reference evapotranspiration (ET_o) (Allen et al., 1998) early in the 2006 growing season (Fig. 6) may have caused the coarse-textured Amarillo sandy loam soil to heat and dry more rapidly compared with the fine-textured Pullman clay loam and Ulysses silt loam soils, which could have limited cotton root development and subsequently water use (Tolk and Howell, 2010). Lower early and late season ET_o in 1999 compared with 1997 and 1998 may have reduced stress on grain sorghum in the Pullman clay loam soil and allowed greater root development and water use (Fig. 4). In comparable limited irrigation studies at performed at two different locations, Musick and Sletten (1966) reported lower grain yields of grain sorghum grown in a Pullman soil at Bushland, TX, compared with sorghum grain yields grown in a Ulysses–Richfield soil complex near Garden City, KS. However, at the same location, Tolk et al. (1997) had similar grain yields of sorghum under limited irrigation in the Pullman and Ulysses soils. The difference in yield results comparing soil textural classes may have been due to the gross climatic differences between the two locations.

Cotton tended to use an average of 0.034 $m^3\ m^{-3}$ and grain sorghum 0.028 $m^3\ m^{-3}$ more soil water than maize to a 2.2-m depth in the three soils. Maize has had very limited success as a dryland and limited irrigation crop in Pullman clay loam soil (Musick and Dusek, 1980; Tolk et al., 1998), which our data suggests is related to its inability to extract water efficiently from its rooting zone. Unlike in the Pullman clay loam soil, maize extracted water to $LL_{-1.5}$ to a 1.6-m depth in the Ulysses silt loam and Amarillo sandy loam soils. For the Ulysses silt loam soil, this resulted in greater grain yields in the dryland and limited irrigation treatments compared with crops grown similarly in the Pullman clay loam (Tolk et al., 1998). However, in the Amarillo sandy loam soil, grain yields of maize were similar to those from the Pullman clay loam in that study, possibly due to the more fully developed Bt horizon of the Amarillo sandy loam soil, which is more similar to that of the Pullman than to that of the Ulysses. The limited use of available soil water by maize in the Pullman soil illustrates why maize requires irrigation to achieve adequate yields on the Pullman clay loam soil (Howell et al., 1995; Tolk et al., 1998). Cotton and grain sorghum with their ability to use soil water up to and beyond $LL_{-1.5}$ make these crops more suitable to limited irrigation and dryland production in the semiarid southern High Plains.

CONCLUSIONS

This study presents an analysis of the lower limits of water use for cotton, grain sorghum, and short season maize grown in lysimeters containing monolithic soil cores of the Amarillo sandy loam, Pullman clay loam, and Ulysses silt loam soil series in the semiarid southern High Plains. The LL_F is particularly important for determining water availability in limited irrigation or dryland production, where yield is strongly influenced by a crop's ability to fully use available soil water. Significant differences between LL_F and $LL_{-1.5}$ did occur. For a 2.2-m profile, the LL_F of cotton

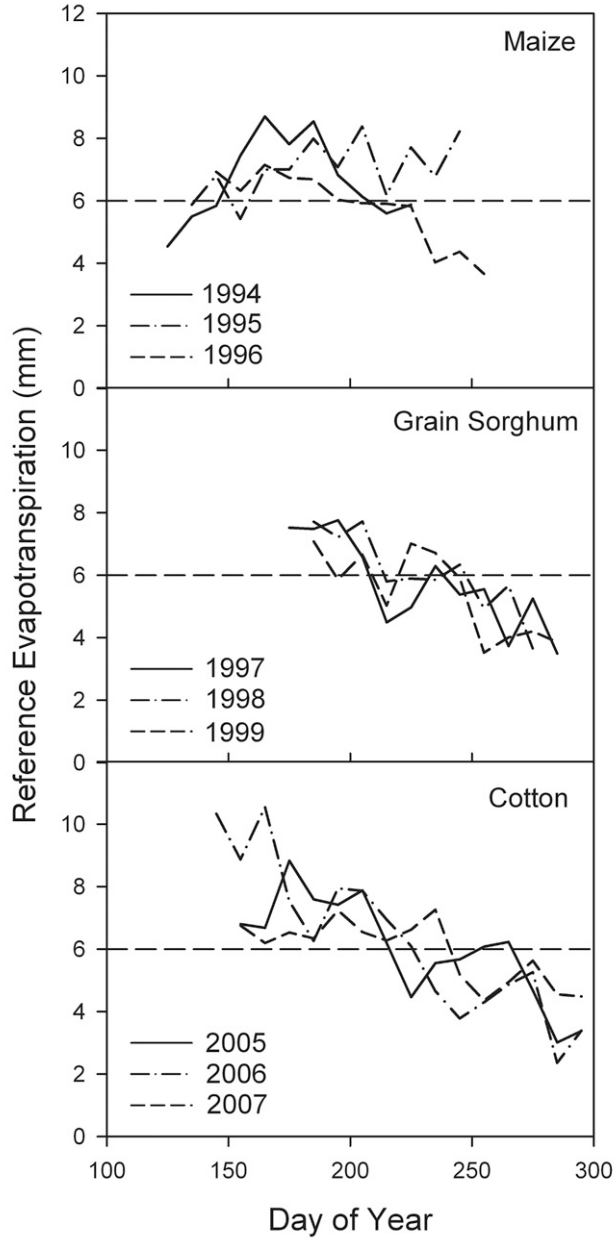

Fig. 6. Reference evapotranspiration from planting through harvest for the three cropping seasons of maize, grain sorghum, and cotton.

was significantly smaller than the $LL_{-1.5}$ of the silt loam and the sandy loam soils, and the LL_F of grain sorghum significantly smaller than the $LL_{-1.5}$ of the silt loam soil. However, the LL_F of maize was significantly larger than the $LL_{-1.5}$ of the clay loam. The LL_F of the other soil and crop combinations were similar to $LL_{-1.5}$. While the relationship of crop LL_F to a soil's $LL_{-1.5}$ varied within a soil textural class, the crops did respond similarly to changes in soil textural classes, with the crop LL_F tending to decrease in relation to $LL_{-1.5}$ in the order of clay loam, sandy loam, and silt loam. When comparing among crops within each soil textural class, cotton and grain sorghum tended to use more soil water, and at greater depths, compared with maize. Reduced water use by the three crops in the lower soil profiles of the Pullman clay loam and Amarillo silt loam soils compared with the Ulysses silt loam soil may have been due to the presence of

calcium carbonate horizons. Interannual variations in climate among the 3 yr of measurements for each crop interacted with soil textural class and crop type to produce differences in LL_F among years of certain soil and crop combinations. Crop type, soil textural class, soil chemical layers, and interannual variations in climate all affected the ability of a crop to use soil water up to and beyond $LL_{-1.5}$.

ACKNOWLEDGMENTS

We would like to thank Dr. Kathleen M. Yeater, Area Statistician, Southern Plains Area, USDA Agricultural Research Service, for her invaluable statistical analyses of these data. I would also like to thank Jennifer Childers and Jim Cresap, biological science technicians, for their hard work in collecting and processing the neutron meter data.

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