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ALTERNATIVE CROPS

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ABSTRACT

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is a drought-tolerant crop that may serve as an alternative summer crop in Nebraska. Field experiments were conducted in 2000 and 2001 near Sidney and Mead, NE, to determine the water use efficiency (WUE) and yield response to water supply at critical developmental stages of pearl millet and grain sorghum [*Sorghum bicolor* (L.) Moench]. Four water regimes were used: (i) no irrigation, (ii) single irrigation at boot stage, (iii) single irrigation at mid–grain fill, and (iv) multiple irrigations. Pearl millet grain yields were 60 to 80% that of grain sorghum. Average grain yields at Mead were 5.1 Mg ha^{-1} for pearl millet and 6.1 Mg ha^{-1} for grain sorghum. At Sidney, average pearl millet yields were 1.9 and 3.9 Mg ha^{-1} in 2000 and 2001, respectively, and average grain sorghum yields were 4.1 and 5.0 Mg ha^{-1} in 2000 and 2001, respectively. Both crops used a similar amount of water (336 and 330 mm in 2000 and 370 and 374 mm in 2001 for pearl millet and grain sorghum, respectively) and responded to irrigation with a linear increase in grain yield as water use increased. Grain sorghum had greater WUE than pearl millet (12.4–13.4 kg vs. 5.1–10.4 kg grain ha^{-1} mm^{-1}). Pearl millet, with lower and less stable yields, does not currently have the potential to be a substitute crop for grain sorghum in Nebraska.

Winter wheat–fallow is the prevalent cropping system in the semiarid Central Great Plains, and water is the most limiting resource for dryland crop growth (Smika, 1970). Producers in this region include summer fallow in the rotation to stabilize crop production in a highly variable climate (Lyon et al., 1995). However, precipitation storage efficiency during fallow is least during summer periods when precipitation is greatest (Farahani et al., 1998; Anderson et al., 1999). Therefore, a different approach to water conservation and efficient use of precipitation is needed. The most direct and practical solution to improving efficient use of precipitation may be to include a summer crop in the year following winter wheat that would make better use of summer precipitation (Peterson et al., 1996). Studies have been conducted to investigate more intensive crop management systems involving alternative summer crops in rotation with winter wheat (Anderson et al., 1999; Farahani et al., 1998; Norwood, 1999; Plett et al., 1991). High temperatures and potential evapotranspiration (ET) limit the number of crops grown in this region. Corn (*Zea mays* L.), sunflower (*Helianthus annuus* L.), soybean [*Glycine max* (L.) Merr.], and proso millet (*Panicum miliaceum* L.) are possible crops for inclusion in more intensive cropping systems. Grain sorghum was found to be more suitable than corn, soybean, or sunflower due to greater and more consistent yields.

Pearl millet, with its short growth cycle and drought tolerance, may be a better alternative crop than grain sorghum for western Nebraska and a possible diversification crop in eastern Nebraska cropping systems. Plett et al. (1991) indicated that pearl millet did not perform well compared with grain sorghum and corn when grown in western Nebraska. However, those hybrids were experimental, and cool night temperatures resulted in problems with seed set. Progress has been made in pearl millet breeding, and hybrids less sensitive to cold night temperatures have been developed. Pearl millet is usually grown as a rainfed crop on sandy soil in the semiarid tropics of the world, and it can produce yield in water-stressed environments where grain sorghum fails (BOSTID, 1996).

Evapotranspiration, the water removed from soils by evaporation and plant transpiration, is directly related to yield in most cereals. Reduction in yield may occur when irrigation and rainfall combined are insufficient to meet ET demand. Smaller plants transpire less water than larger ones because ET increases with increases in leaf surface area (Cothren et al., 2000). Timing of water supply generally has a larger effect on grain yield than total water for many crops (Shaw, 1988). Both pearl millet and grain sorghum productivity are most sensitive to water stress during flowering and grain filling (Garrity et al., 1983; Hattendorf et al., 1988). Studies on irrigated pearl millet are limited and focused on a single irrigation without consideration of soil water content before irrigation (Chaudhuri and Kanemasu, 1985). We hypothesized that pearl millet would yield better under water stress or shorter growing season conditions than grain sorghum and that the two crops may differ in their response to a range of environmental conditions. The range of environmental conditions included years, locations, and water regimes. The latter is the most limiting factor in rainfed crop production. The objectives of this study were to (i) evaluate pearl millet as a possible alternative crop in Nebraska and (ii) determine the WUE and yield response to water supply for pearl millet and grain sorghum.

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Abbreviations: ET, evapotranspiration; ET_p, potential evapotranspiration; WUE, water use efficiency.

MATERIALS AND METHODS

Field experiments were conducted in western and eastern Nebraska in 2000 and 2001. The western Nebraska experiment was conducted at the University of Nebraska High Plains Agricultural Laboratory located 8 km north of Sidney, NE (41°12′ N, 103°0′ W at 1317 m elevation). Long term (30-yr average) mean growing season (May to September) precipitation is 285 mm, and average last spring freeze and first autumn freeze dates are 14 May and 21 September. Soil at the site is a Keith silt loam (fine-silty, mixed mesic Aridic Argiustoll), and its chemical properties are presented in Table 1. Available water holding capacities for the soil are 0.51 to 0.58 cm cm^{-1} for the 0- to 25-cm soil depth, 0.46 to 0.56 for the 25- to 58-cm soil depth, and 0.51 to 0.56 for the 58- to 152-cm soil depth (USDA-NRCS and Univ. of Nebraska–Lincoln, 1997).

The eastern Nebraska experiment was conducted at the University of Nebraska Agronomy Farm near Mead, NE (41°8′24″ N, 96°17′24″ W at 369 m elevation). Mean growing season precipitation is 480 mm. Soil at the site is a Sharpsburg silty clay loam (fine, smectitic, mesic, Typic Argiudoll), and its chemical properties are presented in Table 1. Available water holding capacities for the soil are 0.53 to 0.58 cm cm^{-1} for the 0- to 36-cm soil depth and 0.46 to 0.51 cm cm^{-1} for the 36- to 114-cm soil depth (USDA-NRCS and Univ. of Nebraska–Lincoln, 1995).

The treatment structure was a 4 × 2 factorial in the western and eastern Nebraska experiments, which were dramatically different production environments. Factor 1 consisted of four water regimes to reflect range of environments possible at both locations: (i) no irrigation, (ii) single irrigation at boot stage, (iii) a single irrigation at mid–grain fill, and (iv) multiple irrigation throughout the season. Factor 2 consisted of two crops: a pearl millet hybrid ‘68A × 086R’, one of the last pearl millet hybrids released by the breeding program at the University of Nebraska Lincoln, and a grain sorghum hybrid, ‘DK 28E’, with a short maturity cycle similar to pearl millet. The experimental designs for the two sites were different due to difference in irrigation systems. At Sidney, the irrigation system was a self-propelled, lateral-move system with individually controlled drop nozzles, which allowed the experiment to be conducted as a randomized complete block design with four replications. Plot size was 9.12 m (12 rows) wide and 14.2 m long with 3-m alleys between plots. At Mead, a furrow irrigation system was used, and the experiment was conducted as a randomized complete block design with a split-plot treatment arrangement and four replications. The whole-plot treatments were the four water regimes, and the split-plot treatment was crop. Plot size was 6.8 m wide (nine rows, 76 cm apart) and 9.1 m long.

At Sidney, both pearl millet and grain sorghum were no-till–planted into wheat stubble using a 76-cm row spacing. Crops were planted on 8 June 2000 and on 11 June 2001. Pearl millet plots were thinned 3 wk after planting. Final plant stands were 111 700 ± 6 890 plants ha^{-1} for pearl millet and 112 500 ± 6 890 plants ha^{-1} for grain sorghum in 2000 and 135 200 ± 10 880 plants ha^{-1} for pearl millet and 126 800 ± 10 880 plants ha^{-1} for grain sorghum in 2001. Soil test results indicated that N application was not needed in either year. However, 45 kg N ha^{-1} was hand- broadcasted as urea (46–0–0) to all plots before planting in 2000. Weeds were controlled with propazine [6-chloro-*N,N*-bis(1-methylethyl)-1,3,5-triazine-2,4-diamine] applied pre-emergence at 1.12 kg ha^{-1} and by hand hoeing.

At Mead, the experimental area was fall chisel-plowed, field cultivated, and roller packed before planting to prepare a seedbed. Pearl millet and grain sorghum were planted in 76-cm rows on 1 June 2000 and 18 June 2001 at 215 000 ± 10 500 seeds ha^{-1}. These seeding rates resulted in plant population of 175 600 ± 2 250 plants ha^{-1} for grain sorghum and 174 000 ± 8 700 plants ha^{-1} for pearl millet. Fertilizer was broadcast-applied and incorporated before planting at the rates of 112 kg N ha^{-1} in both years and 21.4 kg P ha^{-1} in 2000. Weeds were controlled with herbicide application, cultivation, and hand hoeing. Herbicides included atrazine [6-chloro-*N*-ethyl-*N*’-(1-methyl)-1,3,5-triazine-2,4-diamine] applied pre-emergent at 1.2 kg ha^{-1} followed by 0.6 kg ha^{-1} metolachlor [2-chloro-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide] and 0.6 kg ha^{-1} bentazon [3-(1-methylethyl)-(1*H*)-2,1,3-benzothiadiazin-4(3*H*)-one 2,2-dioxide] applied when pearl millet reached the three-leaf stage. The insecticide tefluthrin {(2,3,5,6-tetrafluoro-4-methylphenyl) methyl[1α, 3α (*Z*)-(+)-]-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate} was applied at 0.5 kg ha^{-1} to control green bug (*Schizaphis graminum* Rondani) infestation in 2001.

Table 1. Soil chemical properties of the experimental sites.

Sidney			Mead		
Soil depth	**2000**	**2001**	**Soil depth**	**2000**	**2001**
cm	mg kg^{-1} NO_3–N		cm	— mg kg^{-1} NO_3–N —	
0–30	**5.6**	**3.4**	**0–15**	**5.1**	**7.7**
30–61	**11.2**	**3.3**	**15–61**	**2.9**	**4.4**
61–122	**26.1**	**14.4**	**61–91**	**1.7**	**3.5**
			91–122	**2.0**	**3.0**
		Soil surface to 20 cm			
pH	**7.2**	**6.8**		**5.7**	**6.3**
Soil organic C, mg kg^{-1}	**21**	**20**		**30**	**30**
P, mg kg^{-1}	**173**	**54**		**30**	**43**
K, cmol kg^{-1}	**2.6**	**2.6**		**1.2**	**1.2**

At Mead, the decision to irrigate in all irrigation treatments was based on physical observation of crop stress and soil water content using the feel method (USDA-NRCS, 1998). Furrow irrigation was used, with flow rate being controlled by adjusting the irrigation pump speed and openings. At the beginning of each irrigation, water was applied at the greatest rate (1 200 ± 20 L min^{-1}) that could be used without causing excessive erosion of the furrow, followed by slower application. Multiple-irrigation plots were irrigated on 25 July, 14 Aug., 16 Aug., and 30 Aug. in 2000 and on 26 July, 3 Aug., and 22 Aug. in 2001. Main plots were irrigated on 25 July 2000 and 3 Aug. 2001 for boot irrigation treatments and on 16 Aug. 2000 and 22 Aug. 2001 for mid–grain fill irrigation treatments. Each irrigation brought the soil profile to field capacity.

At Sidney, two 1.52-m-long aluminum access tubes were installed in the central area of each plot. A neutron probe (Campbell Pacific 503 DR, Campbell Pacific, Pacheco, CA) was used to monitor soil moisture weekly in 30-cm increments during the growing season and immediately after harvest. Soil water content in the surface 30 cm was measured gravimetrically. In all irrigated treatments, water was applied to bring the soil water level to 80% of the available soil water capacity (318 mm for 152 cm soil profile). Water was applied whenever available soil water fell below 70% of available soil water capacity in the multiple-irrigation treatment. Soil available water capacity was defined as the difference between the amount of soil water at field capacity and the amount at the wilting point and was 318 mm for the surface 1.5 m of soil. Water applications were made in 25-mm increments. Water applications were made with a 1-d interval between applications to avoid runoff. The entire experiment was irrigated with 25 mm of water after planting to promote germination in 2000. The initial water measurement was made after this application. A total of 305 mm of water was applied in the multiple-

Table 2. Growing season monthly average temperatures and total precipitation and evapotranspiration at Sidney, NE. Source: High Plains Regional Climate Center, University of Nebraska, Lincoln.

	Temperature											
	2000		2001		30-yr avg.		Precipitation			Potential evapotranspiration		
Month	Low	High	Low	High	Low	High	2000	2001	30-yr avg.	2000	2001	30-yr avg.
	°C						mm					
May	7.0	22.7	6.1	19.8	5.6	21.4	45	100	77	236	193	196
June	10.7	28.9	10.5	27.5	11.2	27.4	27	36	73	300	243	230
July	15.3	33.1	16.2	32.3	14.4	31.3	18	92	62	289	255	275
August	14.8	33.1	13.6	31.4	12.9	29.9	12	61	39	292	257	243
September	8.2	25.9	9.4	25.7	7.2	24.6	39	65	34	229	191	187
Total							141	354	285	1347	1114	1131

irrigation treatment in 2000 and 102 mm was applied in 2001. The total amount of supplied water for the boot stage irrigation treatment was 127 mm in 2000 and 25 mm in 2001. The total amount of water applied for the grain fill irrigation treatment was 127 mm in 2000 and 76 mm in 2001.

Evapotranspiration, considered to be water used (WU), was estimated using $WU = SWP + GSP + AW - SWH - R$, where SWP is soil water at planting, GSP is growing season precipitation, AW is applied water, SWH is soil water at harvest, and R is deep percolation and runoff. Observations suggested that deep percolation and runoff were negligible in this study. Water use efficiency was calculated on a grain yield and biomass basis by dividing grain yield by water used and the total aboveground biomass by water used.

A time-scaled fraction of growing season defined as the thermal (or growing degree) units accumulated from planting to each of these growth stages was used. Thermal units were calculated as the mean daily air temperature (maximum plus minimum divided by 2) minus a base temperature (10°C for both pearl millet and grain sorghum; Ong, 1983). Any daily value of thermal units that was negative was considered to be 0°C when accumulating thermal units for the season.

Two central rows, 3 m long, were hand-harvested from each plot for panicles and stover weight, grain yield, total aboveground biomass, and harvest index determination at both sites. Panicles were weighed and threshed separately, and grain yields were corrected to 140 g kg^{-1} water content. Total aboveground biomass was calculated by summing nonthreshed panicle weights and stover weights.

Data from Sidney and Mead were analyzed separately due to difference in irrigation methods and experimental design. Within each location, analysis of variance to determine the significance level of interactions between treatments and their main effect was done with the mixed model procedure of SAS as presented by Littell et al. (1996) for individual years or pooled across years when Hartley's test for homogeneity of variances (Dowdy and Wearden, 1991) allowed it. Single degree-of-freedom contrasts were performed using SAS procedures. Linear regression analysis was used to determine the response of grain yield and total aboveground biomass to seasonal water use.

RESULTS AND DISCUSSION

The 30-yr average growing season rainfall at Mead is 68% greater than at Sidney (Tables 2 and 3). During the 2 yr of this experiment, high and low temperatures were near long-term averages at Mead and slightly greater than average at Sidney (Tables 2 and 3). Rainfall was 50% less than the long-term seasonal average at Sidney and 25% less at Mead in 2000. Rainfall was above the long-term average for both locations in 2001. However, Sidney rainfall was 24% above the long-term average and evenly distributed throughout the season while above-average rainfall was received only in May at Mead. The 30-yr average growing season potential evapotranspiration (ET_p) at Sidney is 40% greater than at Mead, and the ET_p/precipitation ratio, an indicator of water-stressed environment, is 4.0 for Sidney and 1.7 for Mead (Tables 2 and 3). This ratio was 9.6 in 2000 and 3.2 in 2001 at Sidney while it was 2.6 in 2000 and 2.1 in 2001 at Mead.

Differences between pearl millet and grain sorghum phenology were more pronounced in 2000 than in 2001. Both crops reached boot and mid–grain fill stages earlier in 2001 than in 2000. Pearl millet reached boot, mid–grain fill, and physiological maturity earlier than grain sorghum at Mead. At Sidney, water regime affected crop phenology in 2000 but not in 2001. Pearl millet in the multiple-irrigation treatment reached boot stage at 633 growing degree days while in the other water treatments, the boot stage was reached at 706 growing degree days (data not presented).

Table 3. Growing season monthly average temperatures and total precipitation and evapotranspiration at the Agronomy Farm near Mead, NE. Source: High Plains Regional Climate Center, University of Nebraska, Lincoln.

	Temperature											
	2000		2001		30-yr avg.		Precipitation			Potential evapotranspiration		
Month	Low	High	Low	High	Low	High	2000	2001	30-yr avg.	2000	2001	30-yr avg.
	°C						mm					
May	11.2	26.3	11.5	23.4	10.6	23.4	70	230	105	207	196	167
June	14.4	28.5	15.5	28.0	16.2	29.1	152	40	106	215	218	189
July	14.4	29.3	19.8	31.9	19.2	31.7	88	25	87	163	191	185
August	19.0	31.1	17.1	30.9	17.7	30.1	43	79	92	166	194	145
September	11.1	28.0	11.2	25.0	12.3	25.0	15	67	90	210	130	119
Total							369	440	480	960	929	805

Grain and Biomass Yields

Grain and aboveground biomass yields for pearl millet and grain sorghum were greater at Mead than at Sidney (Table 4). Crop and water treatments did not interact for grain or aboveground biomass yields at either location. Pearl millet yielded less than grain sorghum in both years and locations. The grain yield difference between the two crops was greatest in 2000 at Sidney where pearl millet yield averaged 46% of the average grain sorghum yield. Pearl millet aboveground biomass was also less than that of grain sorghum at Sidney in 2000. Andrews et al. (1998) reported that when grown in sorghum production environments in the Great Plains without irrigation, pearl millet yields were 80 to 85% of grain sorghum hybrids of comparable maturity, averaging 2 to 3 Mg ha^{-1} in regional tests. In 2001 at Sidney, and 2000 and 2001 at Mead, overall pearl millet grain yields were 78, 84, and 82% of grain sorghum yields, respectively (Table 4).

Irrigation increased grain yield at both locations in both years (Table 4), but biomass production was increased by irrigation only at Sidney in 2000. Single irrigation at boot and mid–grain fill stages resulted in less grain and aboveground biomass yields compared with the multiple-irrigations treatment at Sidney. Even though these are the most sensitive stages to water stress, both crops responded to irrigation at all growth stages. At Mead, grain yield with a single irrigation was similar to that obtained with the multiple-irrigation treatment in 2000. In 2001, with less June and July precipitation, supplemental water at boot and mid–grain fill stages was inadequate to produce grain yield equal to the multiple-irrigations treatment. Grain yield was greater with a single irrigation at mid–grain fill than at boot stage at Sidney while at Mead in 2000, greater grain yield was produced with irrigation at the boot stage. No grain yield difference between boot and mid–grain fill water applications was present at Mead in 2001. The two single irrigation treatments produced the same amount of aboveground biomass in both locations during the 2 yr of study.

Hartley's test for homogeneity of variances (Dowdy and Wearden, 1991) indicated that across-years analysis was appropriate for Mead data but not Sidney. Water regime and crop × year interaction effects were present for grain and biomass yield at Mead. In the no-irrigation treatment at Mead, pearl millet grain yield was about 91% of grain sorghum yield, which is greater than the 80 to 85% reported by Andrews et al. (1998) and Christensen et al. (1987). Compared with the no-irrigation treatment, irrigation increased grain yield, but not aboveground biomass, of both crops. However, the increase in pearl millet grain yields was less than that of grain sorghum. A single irrigation at the boot stage increased pearl millet grain yield by 2% and grain sorghum yield by 13% compared with no irrigation. With this treatment, pearl millet grain yield was about 82% that of grain sorghum. When water was applied at mid–grain fill, pearl millet and grain sorghum produced 10 and 19% more grain than with no irrigation. In the multiple-irrigations treatment, pearl millet produced 8% more than with no irrigation. Grain sorghum in the multiple-irrigation treatment produced 6.7 Mg ha^{-1}, an increase of 26% compared with the no-irrigation treatment. In the multiple-irrigation treatment, pearl millet grain yield was 78% of grain sorghum yield.

Pearl millet was less responsive than grain sorghum to irrigation. Pearl millet had lower grain yield than grain sorghum in all of the wide range of production environments resulting from the 2 yr, two locations, and four water regimes. Our experiments using new hybrids support and extend previous reports that found that grain sorghum is better adapted than pearl millet in eastern Nebraska (Palé et al., 2003) and Kansas (Chaudhuri and Kanemasu, 1985; Christensen et al., 1987). This included the high-elevation, short growing season, low-rainfall environment in western Nebraska and a wide range of production environments resulting from imposing different water regimes at both locations.

Water Use and Water Use Efficiency

Pearl millet and grain sorghum under the different irrigation treatments did not differ in water use; crop ×

Table 4. Mean pearl millet and grain sorghum grain yield and aboveground biomass, as affected by water regime at Sidney and Mead, NE.

	Sidney				Mead			
	2000		2001		2000		2001	
Treatments	Grain	Biomass	Grain	Biomass	Grain	Biomass	Grain	Biomass
	Mg ha^{-1}							
Crop								
Pearl millet	1.9	8.0	3.9	14.6	4.8	13.1	5.3	16.7
Sorghum	4.1	9.1	5.0	14.6	5.7	12.8	6.5	15.5
Water regime								
No irrigation	1.4	5.5	3.6	14.3	4.9	12.3	5.2	15.7
Multiple irrigation	4.9	13.4	5.5	14.0	5.5	13.8	6.5	16.5
Boot irrigation	2.7	8.5	4.1	15.8	5.6	12.7	5.8	16.2
Mid–grain fill irrigation	3.0	8.6	4.6	14.2	5.1	13.1	6.0	16.1
F test and contrast probabilities	$P > F$							
Crop (C)	<0.01	<0.01	<0.01	0.99	<0.01	0.45	<0.01	<0.01
Water regime (WR)	<0.01	<0.01	<0.01	0.02	0.01	0.11	<0.01	0.38
C × WR	0.14	0.12	0.62	0.21	0.12	0.90	0.08	0.21
Contrasts								
Nonirrigated vs. irrigated	<0.01	<0.01	<0.01	0.45	<0.01	0.09	<0.01	0.17
Multiple vs. partial irrigation	<0.01	<0.01	<0.01	<0.01	0.32	0.08	0.01	0.30
Boot vs. mid–grain fill irrigation	0.39	0.98	<0.01	0.73	0.02	0.49	0.47	0.82

Table 5. Mean pearl millet and grain sorghum water use and water use efficiency as affected by water regime at Sidney, NE.

	2000			2001		
		Water use efficiency			Water use efficiency	
	Water use	Grain	Biomass	Water use	Grain	Biomass
	mm	kg ha^{-1} mm^{-1}		mm	kg ha^{-1} mm^{-1}	
Crop						
Pearl millet	336	5.1	24.1	370	10.4	39.6
Grain sorghum	339	11.8	28.5	374	13.4	39.3
Water regime						
No irrigation	227	6.2	24.3	327	10.9	43.6
Multiple irrigation	476	10.2	28.0	444	12.5	35.6
Boot irrigation	326	8.1	26.1	357	11.4	39.1
Mid–grain fill irrigation	319	9.4	26.8	360	12.9	39.4
***F* test and contrast probabilities**	$P > F$					
Crop (C)	0.34	<0.01	0.03	0.37	<0.01	0.77
Water regime (WR)	<0.01	0.16	0.57	<0.01	<0.01	<0.01
C × WR	<0.01	0.19	0.45	0.50	0.72	0.58
Contrasts						
Nonirrigated vs. irrigated	<0.01	<0.01	0.23	<0.01	<0.01	<0.01
Multiple vs. partial irrigation	<0.01	0.16	0.52	<0.01	0.30	0.01
Boot vs. mid–grain fill irrigation	0.19	0.26	0.81	0.70	<0.01	0.83

irrigation treatment interaction effects on water use occurred in 2000 but not 2001 at Sidney (Table 5). The interaction in 2000 was due to grain sorghum using 18 mm more water with a single irrigation at boot stage than with a single irrigation at mid–grain fill while water use was similar for pearl millet for the same irrigation treatments. More water was used by pearl millet and grain sorghum in 2001 than in 2000 due to greater soil water availability at planting and greater rainfall during the growing season in 2001 (Table 2). The amounts of water used by the two crops were similar to those reported by Hattendorf et al. (1988) and less than reported by Chaudhuri and Kanemasu (1985) for well-watered conditions. In our experiment, the two crops did not differ in the amount of water used during the two growing seasons even though grain sorghum produced more grain yield in both years and greater biomass in 2000. The two crops did not differ in soil water depletion; the soil water content at planting (201 ± 3 mm in 2000 and 239 ± 2 mm in 2001 for pearl millet and 204 ± 3 mm in 2000 and 238 ± 2 mm in 2001 for grain sorghum) and after harvest (123 ± 2 mm in 2000 and 168 ± 3 mm in 2001 for pearl millet, 122 ± 2 mm in 2000, and 163 ± 3 mm in 2001 for grain sorghum) were similar in both years.

Water use at Sidney was influenced by irrigation in both years. Differences in water use among water treatments were greater in 2000 than in 2001. The amount of water used by the crops in the no-irrigation and single-irrigation treatments was always less than with the multiple-irrigation treatment (Table 5). These results indicate that even with the good rainfall conditions of 2001, water requirement of the two crops was not fulfilled in the no-irrigation or single-irrigation treatments. Even though the two crops are drought tolerant, they are able to use additional water to increase yield. More water was used when supplemental water was applied at mid–grain fill than when applied at boot stage, but this difference was not significant in 2001. These results indicate that the crops' water demand was likely greater during this period because of greater water demand for kernel growth.

In both years, pearl millet and grain sorghum grain yield increased linearly with increased water use at Sidney (Fig. 1). Both pearl millet and grain sorghum used water more efficiently in 2001 than in 2000 for the production of grain and biomass (Table 4). Pearl millet used the same amount of water as grain sorghum but produced less grain yield. Therefore, pearl millet had lower WUE than grain sorghum, except for biomass WUE in 2001. Pearl millet grain WUE was only 41% that of grain sorghum, but biomass WUE for pearl millet was 81% as efficient as that for grain sorghum in 2000. Water use efficiency was greater for both crops in 2001. Pearl millet and grain sorghum had the same biomass WUE, but pearl millet grain WUE was 78% that of grain sorghum in 2001. It was expected that pearl millet would have similar or better grain yield than grain sorghum in 2000. Pearl millet was able to improve its yield and WUE with improved conditions. Christensen et al. (1987) found that in unfavorable environments, pearl millet had better yield, and its response to changing environment was similar to that of grain sorghum. Grain sorghum had a more stable and consistent response to water use and production than pearl millet in this study.

Water use efficiencies were influenced by water regime treatments only in 2001. In 2000, crops in the no-irrigation treatment had similar biomass WUE but lower grain WUE than when supplemental water was applied (Table 5). Crops in the no-irrigation treatment had lower grain WUE, and greater biomass WUE in 2001, indicating that supplemental water helped increase the proportion of grain relative to total biomass (i.e., the harvest index).

Pearl millet had a greater change in biomass WUE to grain WUE ratio than grain sorghum, with a change from 4.7 in 2000 to 3.8 in 2001, while for grain sorghum, this ratio changed from 2.4 in 2000 to 2.9 in 2001. These results are similar to what was reported by Chaudhuri and Kanemasu (1985). Pearl millet was less efficient than grain sorghum in partitioning photoassimilates to grain.

Harvest index is a parameter for interpreting agro-

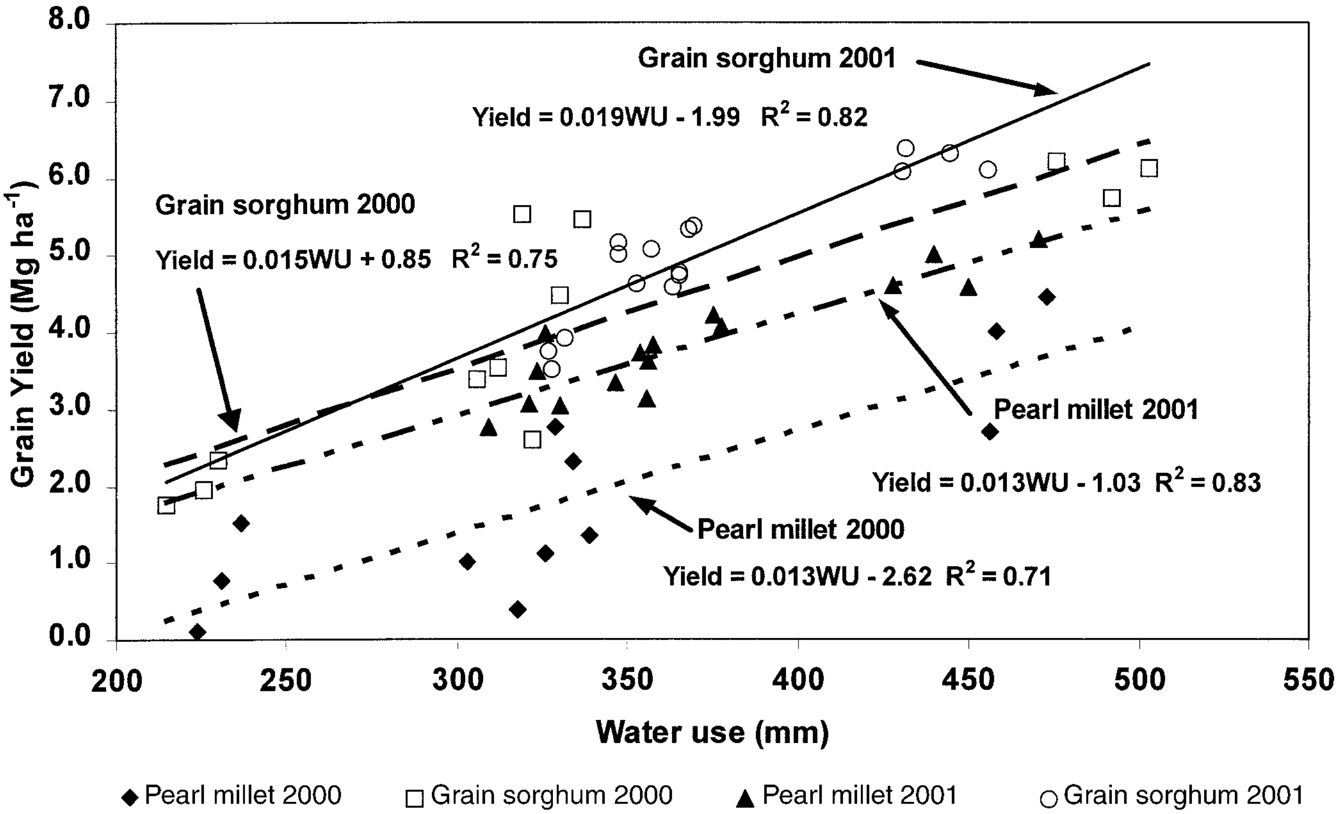

Fig. 1. Grain yield response of pearl millet and grain sorghum to water use at Sidney, NE. Each data point represents plot grain yield. WU, water use.

nomic data with stress effect differences. Prihar and Stewart (1991) suggested that harvest index can be applied as a reference for interpreting useful parameters for comparing crop species or cultivars for their capability to partition photoassimilates to grain within a given environment. Hay and Walker (1989) observed that grain growth can be unresponsive to increased assimilate supply resulting in sink limitation even though its final weight does not reach the potential of the cultivar. The lower harvest index for pearl millet may not be due to source limitation, but rather to the high tillering capacity of pearl millet. New tillers compete with grain fill for photoassimilates, particularly when they are under limited water conditions. In this case, the tillering capacity becomes a disadvantage for pearl millet grain production. Another reason may be pearl millet grain set was limited by low temperature during flowering, as suggested by Christensen et al. (1987). However, during the flowering period in August, temperatures were greater in 2000 compared with 2001, but grain yields were much greater in 2001, indicating that low temperatures were not the reason for the reduced yields in 2000. During the pollination period, greater ET_p was the most probable reason for low yield in 2000.

CONCLUSION

Pearl millet and grain sorghum yields were greater in eastern than in western Nebraska due to better environmental growing conditions, greater rainfall, and higher night temperature. In both environments, pearl millet grain yields were 60 to 80% that of grain sorghum. At Sidney, pearl millet grain yields were much greater in 2001 than in 2000 despite lower night temperature during the pollination period. This indicated that environmental factors other than low temperature were likely the reason for pearl millet's low yield in 2000. Pearl millet and grain sorghum responded to irrigation with a linear increase in grain yield as water use increased. Irrigated environments produced greater grain yield for both crops, especially grain sorghum in 2001. Single irrigation increased grain yield but was not enough to reach the yield obtained with multiple irrigation. With greater grain yield, grain sorghum had greater WUE on a grain basis. A single irrigation at mid–grain fill led to similar WUE as multiple irrigations.

Pearl millet may have lower yield potential across the wide range of environments as a result of limited plant breeding research. Pearl millet production was also less stable and more affected by unfavorable environmental conditions than grain sorghum production, primarily due to instability in harvest index. Pearl millet does not have the potential to be a substitute feed-grain crop for grain sorghum in Nebraska at this time. In addition to market development needs, additional plant breeding efforts are needed to develop greater-yielding hybrids before pearl millet will become a viable crop alternative in Nebraska.

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