

Full Length Research Paper

Grain sorghum water use with skip-row configuration in the Central Great Plains of the USA

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Grain sorghum (*Sorghum bicolor* (L.) Moench) is commonly produced under conditions where soil water deficits frequently occur. Research was conducted at ten (10) site-years from 2005 to 2007 across Nebraska where annual mean precipitation ranges from 350 to 900 mm year⁻¹ to determine the effect of row configuration and plant population on soil water distribution, water extraction patterns, crop water use, and water use efficiency (WUE). Three row configurations including all rows planted (s0), alternate rows planted (s1), and two rows planted alternated and two rows skipped (s2) were evaluated in a complete factorial with two populations. Soil water content was measured to 1200 mm depth biweekly with a neutron moisture meter. Total growing-season precipitation varied from 239 to 452 mm. Stored soil water at physiological maturity with the skip-row configurations were 10 to 35 mm greater than s0 across site-years. Water use efficiency was higher with skip-row configurations at site-years with mean growing-season precipitation < 2 mm day⁻¹, and lower at site-years with mean growing-season daily precipitation > 2.5 mm. Skip-row planting conserves water for the reproductive stages and enhances WUE and yield when water deficits are relatively severe.

Key words: Crop water use, soil water distribution, sorghum, skip-row, water use efficiency.

INTRODUCTION

In semiarid regions, plant-available water is often the most limiting factor for crop growth and yield potential in dry land agriculture. Grain sorghum is known for its drought tolerance and is well adapted to semiarid dry land conditions (Jones and Johnson, 1983; Shackel and Hall, 1984; Pennisi, 2009). Unger and Baumhardt (1999) reported that grain sorghum yield increased by 139% in the southern Great Plains between 1939 and 1997 and attributed 93% of this increase primarily to increased soil water content at planting. Water deficit during the early reproductive and grain filling stages of growth; however, it is a common cause of low grain yield and inefficient water use in the Great Plains (Nielsen et al., 2005; Stone and

Schlegel, 2006). Water supply at reproductive growth stages of grain sorghum has more impact on total grain yield than at the vegetative or ripening stages (Ockerby et al., 2001; Maman et al., 2003). Water stress during boot and flower stages can reduce grain yield by 85% (Craufurd et al., 1993). Sorghum is planted in the semiarid central Great Plains in mid-to-late spring when soil water is usually adequate for good emergence and vegetative growth. Sorghum has the capacity to till, but the number and grain yield of tillers depends on several factors including hybrid, row spacing, row configuration, plant population, and water availability (Berenguer and Faci, 2001; Lafarge et al., 2002; Conley et al., 2005; Maman et al., 2003; Bandaru et al., 2006). As a result, the WUE varies in response to these factors.

In this study, we defined the WUE as the ratio of grain yield to water consumed instead of the definition by Sinclair et al. (1984) that relates the total biomass to

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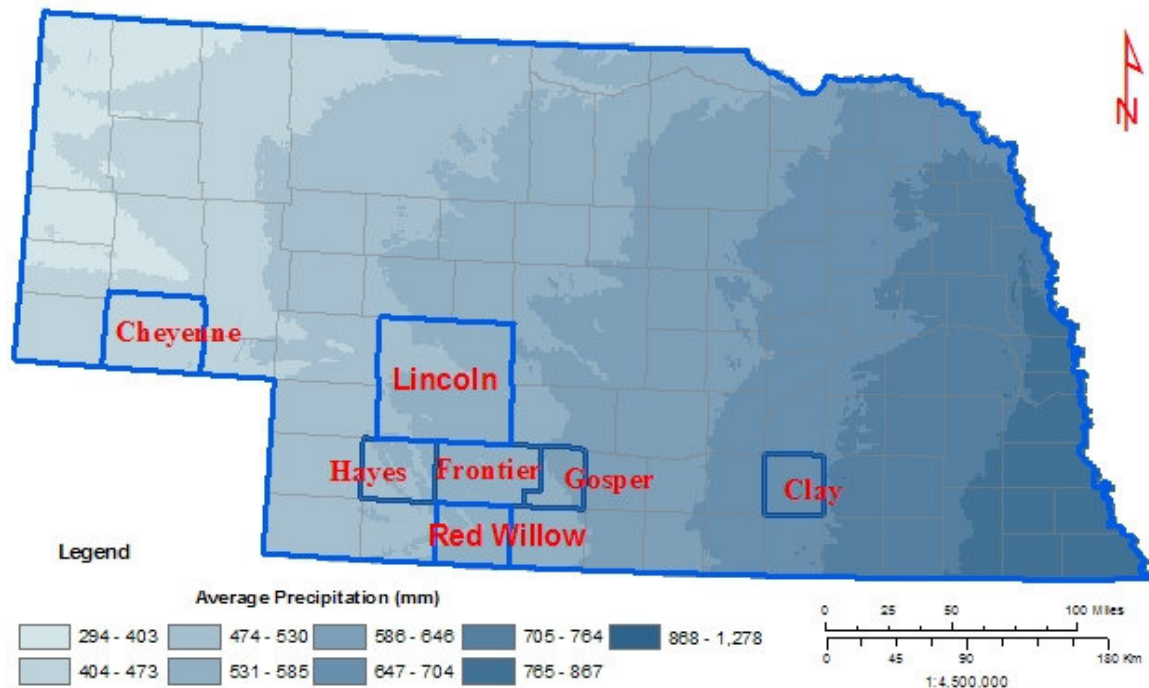


Figure 1. Map of Nebraska, USA showing Counties where the study was carried out.

water consumed. In this respect, WUE can be low when water is used for growth of tillers that do not produce grain. Due to the limited and erratic nature of growing-season precipitation on the Great Plains, several cropping systems have been developed to improve WUE. Nielsen et al. (2005) reviewed several dry land cropping systems including no tillage, reduced tillage, conventional tillage, furrow diking (basin tillage), reduced fallow period, cropping sequence, cropping intensity, crop varieties, residue management practices, and continuous cropping systems with respect to WUE in the Great Plains. They concluded that continuous cropping under dry land conditions in the semiarid Great Plains was risky due to limited and erratic precipitation and high potential evapotranspiration.

A review of several studies conducted in the Great Plains by Sojka et al. (1988) showed a contrasting effect of row spacing on water use efficiency of sorghum. Skip-row planting has been shown to conserve soil water for later use by the crop to improve water use and grain yield (McLean et al., 2003; Routley et al., 2003). In central Queensland, Australia, Collins et al. (2006) reported that skip-row planting had equal or higher grain yield than conventional planting where mean yield potential of grain sorghum was less than 3 mg ha⁻¹. Planting in 1.5- and 2-m wide rows prevented total crop failure and outperformed conventional planting with 1-m row spacing in dry years (Routley et al., 2003; Wish et al., 2005). Bandaru et al. (2006) reported that planting grain sorghum in clumps in water stressed environments increased grain yield in the southern Great Plains. Wide

row spacing with high seeding rates and planting in clumps with three to six plants per hill reduced tiller formation, dry matter yield, and early water use with the benefit of saving soil water in the skipped area for use by plants during flowering and grain fill stages (Thomas et al., 1980; Bandaru et al., 2006).

Grain sorghum production strategies that can improve plant-available water at reproductive growth stages may improve the ratio of grain yield to crop water use (WUE). Routley et al. (2003) has shown that sorghum roots grow in all directions at rates of 15 to 40 mm day⁻¹, depending on the growth stage. If the mean rate of root growth is 25 mm day⁻¹, this would imply that narrow-spaced sorghum will reach and exhaust all the available water early in the growing period if there was no replenishment by rainfall. Conceivably, under low rainfall wider-spaced sorghum would use water stored in the inter-row soil regions to meet its needs during the reproductive stage and hence sustain high yields under dry conditions. The objectives of this study were to evaluate the effects of row configuration and plant population on soil water availability, distribution and extraction patterns, crop water use, and water use efficiency of grain sorghum in the central Great Plains.

MATERIALS AND METHODS

Site characteristics

Field studies were conducted at 10 site-years across Nebraska (Figure 1) from 2005 through 2007. All fields were non-irrigated,

Table 1. Soil series and taxonomic classes information for experimental sites in Nebraska, USA.

Site, soil and agronomic data	Clay	Gosper	Frontier	Hayes	Red willow	Lincoln	Cheyenne
Location and elevation	40°34' N; 98°08' W; 543.3 m	40°28' N; 99°53' W; 732 m	40°40' N; 100°29' W; 829 m	40°30' N; 101°01' W; 922.0 m	40°23' N 100°58' W; 792 m	41°05' N; 100°75' W; 922 m	41°12' N; 103°01' W; 1317 m
Soil series	Crete silt loam	Holdrege silt loam	Hall silt loam	Kuma silt loam	Holdrege & Keith silt loam	Holdrege silt loam	Duroc loam
Taxonomic class	Fine, smectitic, mesic Pachic Arguistolls	Fine-silty, mixed, superactive, mesic Typic Arguistolls	Fine-silty, mixed, superactive, mesic Pachic Arguistolls	Fine-silty, mixed, superactive, mesic Pachic Arguistolls	Fine-silty, mixed, superactive, mesic Typic/Aridic Arguistolls	Fine-silty, mixed, superactive, mesic Typic Arguistolls	Fine-silty, mixed, superactive, mesic Pachic Haplustolls

Table 2. Agronomic information for experimental sites in Nebraska, USA.

Site, soil and agronomic data	Clay	Gosper	Frontier	Hayes	Red willow	Lincoln	Cheyenne
Location and elevation	40°34' N; 98°08' W; 543.3 m	40°28' N; 99°53' W; 732 m	40°40' N; 100°29' W; 829 m	40°30' N; 101°01' W; 922.0 m	40°23' N 100°58' W; 792 m	41°05' N; 100°75' W; 922 m	41°12' N; 103°01' W; 1317 m
Previous crop	Corn	Corn	Corn	Corn	Corn	Corn	Wheat
No. of trials	3	1	1	1	1	1	2
Plant population	75,000; 150,000	50,000; 100,000	50,000; 100,000	50,000; 100,000	50,000; 100,000	50,000; 100,000	50,000; 100,000
Plant date	24 May, 2005; 7 June, 2006; 6 June, 2007;	16 May, 2006;	23 May, 2006;	24 May, 2006;	24 May, 2007;	1 June 1, 2007	1 June, 2006; 5 June, 2007;
Harvest date	14 Oct., 2005; 25 Oct., 2006; 10 Oct., 2007;	31 Oct., 2006;	31 Oct., 2006;	1 Nov., 2006;	2 Oct., 2007;	2 Oct., 2007;	17 Oct., 2006; 3 Oct., 2007;

no-till with corn (*Zea mays* L.) residue from the previous season at all sites except Cheyenne County where the crop residue was wheat (*Triticum aestivum* L. emend. Thell). Soil type varied with site (Table 1). Three planting configurations and two plant populations were evaluated in a complete factorial treatment arrangement in a randomized complete block experimental design with four replications at all site-years. The row configurations included all rows planted, or conventional planting (s0)

using a 76-cm row spacing, and two skip-row configurations: alternate rows planted, or single skip configuration (s1), and two rows planted alternated with two skipped rows, or double skip configuration (s2). Plot size was 54.7 m². Medium (relative maturity of 110 days) maturing grain sorghum cv. Dekalb 42-20 (Monsanto, St. Louis, MO, USA) was planted at the Clay County site, a relatively high rainfall site with annual mean precipitation of 734 mm, and early (relative maturity of 105 days) maturing Dekalb 29-

28 was planted at the remaining site-years. At Clay County, plants were thinned 21 days after emergence to obtain 7.5 and 15.0 plants m⁻² (75,000 and 150,000 plants ha⁻¹, respectively).

At the remaining sites plant population was thinned 21 days after emergence to 5.0 and 10.0 plants m⁻² (50,000 and 100,000 plants ha⁻¹, respectively) (Table 2). Plant population remained constant across all row configurations, resulting in a higher within-row plant density in

skip-row treatments. Fertilizer application was based on the University of Nebraska-Lincoln recommendation for the crop and soil nutrient content before planting at each site (Ferguson, 2000). Gosper, Frontier, Hayes and Red Willow County sites were on cooperating producer's fields while Clay, Lincoln and Cheyenne County sites were located on research stations. Pre-emergence herbicides were soil-applied to control weeds. Plots were machine-harvested and grain yield determined from 18.2 m² in the center of each plot. Yields were standardized at 135 g kg⁻¹ water content.

Soil water content

To monitor the use of soil water of each row configuration during the growing season, neutron probe access tubes were installed at a single point in the center of the skipped area of s1 and s2 configurations (76 and 114 cm from row, respectively) and midway between two rows of the s0 configuration (38 cm from row). Volumetric soil water content was measured beginning from three weeks after planting at two to three week intervals until physiological maturity using a neutron probe (Troxler 4301, Troxler Electronic Labs, Research Triangle Park, NC, USA) at depths of 300, 600, 900 and 1200 mm. Detailed description of neutron probe calibration and soil water content measurement are presented in Abunyewa et al. (2010). Permanent wilting point and field capacity values at various study sites and depths were estimated using the Saxton Equation solution for soil water characteristics (Saxton et al., 1986).

For calculation of crop water use, total growing season water was estimated by adding total growing season precipitation (June to September) to the initial total profile water. Growing-season precipitation, long-term (50-year) average growing-season precipitation, and reference (alfalfa) evapotranspiration (ET_R) data were also collected from nearby automated weather data network sites (www.hprcc.unl.edu/services/). Automated weather data network sites were located 0.05 to 0.2 km from the study site at the Clay, Lincoln and Cheyenne County sites, and 0.1 to 2 km from the study for the remaining sites.

Crop water use and water use efficiency

Crop water use (CWU) was estimated following Routley et al. (2003) and Maman et al. (2003):

$$CWU = W_i - W_f + P - R - D \quad (1)$$

where W_i and W_f are the initial and final soil water storage (mm), P is the growing season precipitation (mm), R is runoff (mm) and D is deep percolation (mm).

With several site-years, there was no significant treatment effect on SWC measured at 1200 mm depth, and individual values of rainfall events were generally low, hence deep percolation and runoff components were considered negligible in CWU calculations. Water use efficiency at physiological maturity was calculated as:

$$WUE = \text{grain yield} / \text{CWU at physiological maturity.}$$

Data analysis

All data were analyzed using the MIXED procedure of SAS (SAS Institute, 2007). Fisher's protected LSD test was used to separate treatment means at $P < 0.05$. Regression analysis was conducted using SigmaPlot v.10 (Systat Software, Inc 2006) to determine the relationship between grain yield and crop water use across site-year. The t-test was used to test for the equality of slope of

regression curves.

RESULTS AND DISCUSSION

Growing-season precipitation and reference (Alfalfa) evapotranspiration

In 2005, the lowest growing-season precipitation period at the Clay County site occurred between 20 and 60 days after planting (DAP). Weekly precipitation accounted for less than 19% of the weekly reference evapotranspiration (ET_R). Total growing-season precipitation in 2006 and 2007 was 87 and 100%, respectively, of the 50-year average precipitation (Figure 2). The total growing-season precipitation in 2006 was 308, 346, 376, and 244 mm at the Frontier, Hayes, Gosper and Cheyenne County sites, respectively, representing 86, 100, 100, and 82% of the 50-year average growing-season precipitation (Figure 2). Most of the 2006 growing-season precipitation at Gosper County occurred later than 70 DAP.

Precipitation rarely met weekly ET_R (Figure 2). Water stress during critical growth stages in the Great Plains is the primary yield limiting factor (Maman et al., 2003; Nielsen et al., 2005). Reduced growing-season precipitation, low plant-available stored soil water, and extremes of temperature during reproductive growth stages can reduce pollination, increase flower abortion, and reduce kernel weight and grain yield (Berenguer and Faci, 2001). Using weather and grain yield data from 1992 to 2005, Staggenborg et al. (2008) reported a positive correlation between sorghum grain yield and growing-season precipitation in the central Great Plains.

Soil water distribution and extraction pattern

Since SWC was measured at a single point midway between rows of s0 and in the center of inter-row area, this may only partially represent total profile soil water of each row configuration. With the assumption that soil water below and near rows will be similarly extracted for all planting configurations, availability of the more distant soil water in the skipped area may reduce risk of crop failure and improve overall WUE. Across all site-years, row configuration effects on total SWC were marginal (except Frontier County site) at 42 DAP (Figure 3) due to a short dry spell experienced during the early stages of the growing season. Row configuration effects were greater at 75 DAP, when SWC with skip-row was higher than with s0 at all sites except Gosper and Hayes County (Figure 3). In 2007, differences in profile total SWC between skip-row and s0 planting were observed only at the Clay County site at 75 DAP and the Cheyenne County site at 120 DAP (Figure 4). The Cheyenne County site in 2007 had lower growing-season precipitation compared to 2006 but more pre-season precipitation and higher profile total SWC throughout the

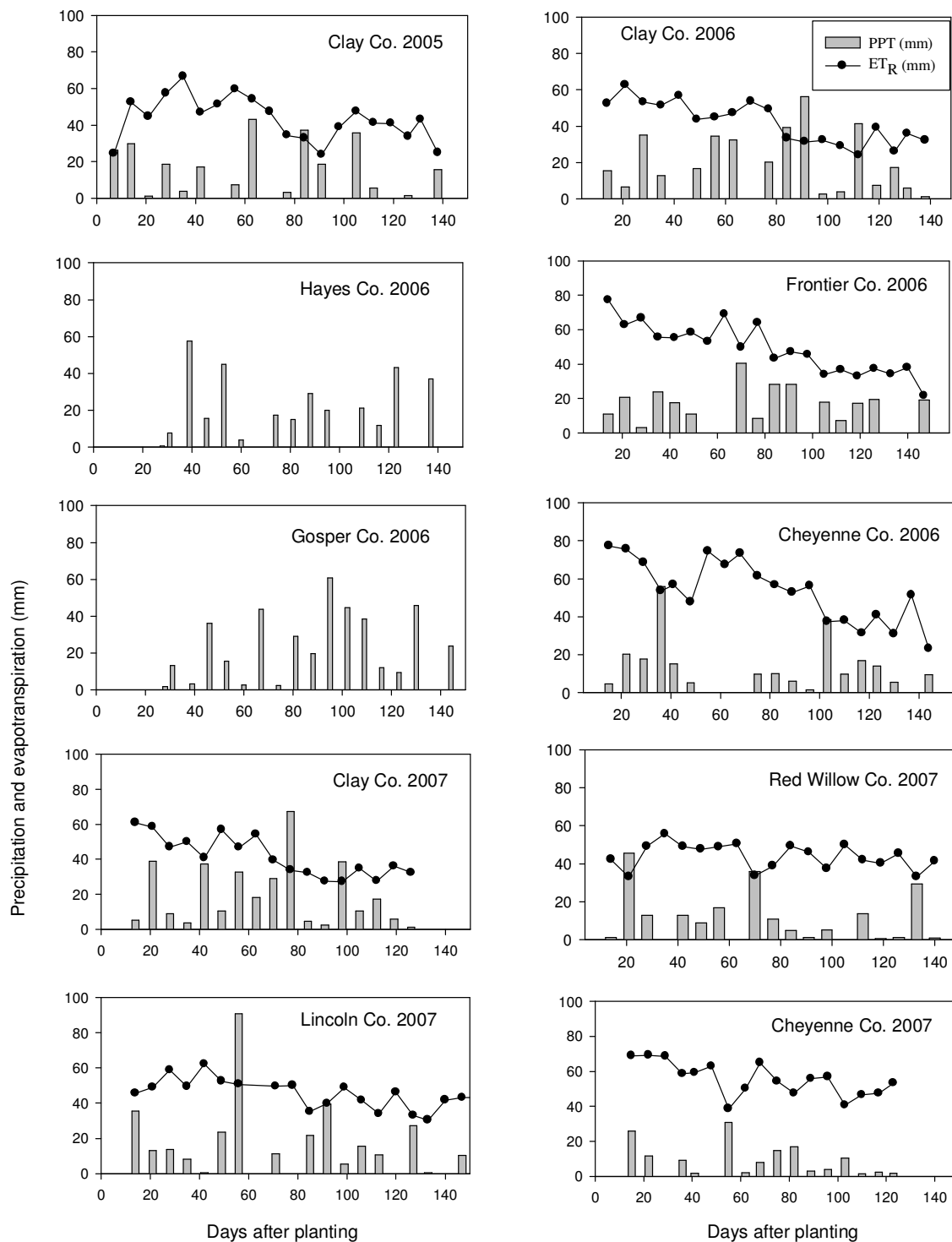


Figure 2. Growing-season precipitation (bar) and reference (Alfalfa) evapotranspiration (ET_R , line) at different sites from 2005 to 2007 in Nebraska. No ET_R values were recorded for Hayes and Gosper County sites by the Nebraska Automatic Weather Data Network.

2007 growing season.

Generally, sites with well distributed growing season precipitation, soil water extraction was mainly limited to the top soil. While sites with less growing season

precipitation and/or dry spells, soil water was extracted from deeper depth across the profile. Since grain sorghum has the capacity to till, lower plant populations were compensated for by having similar number of

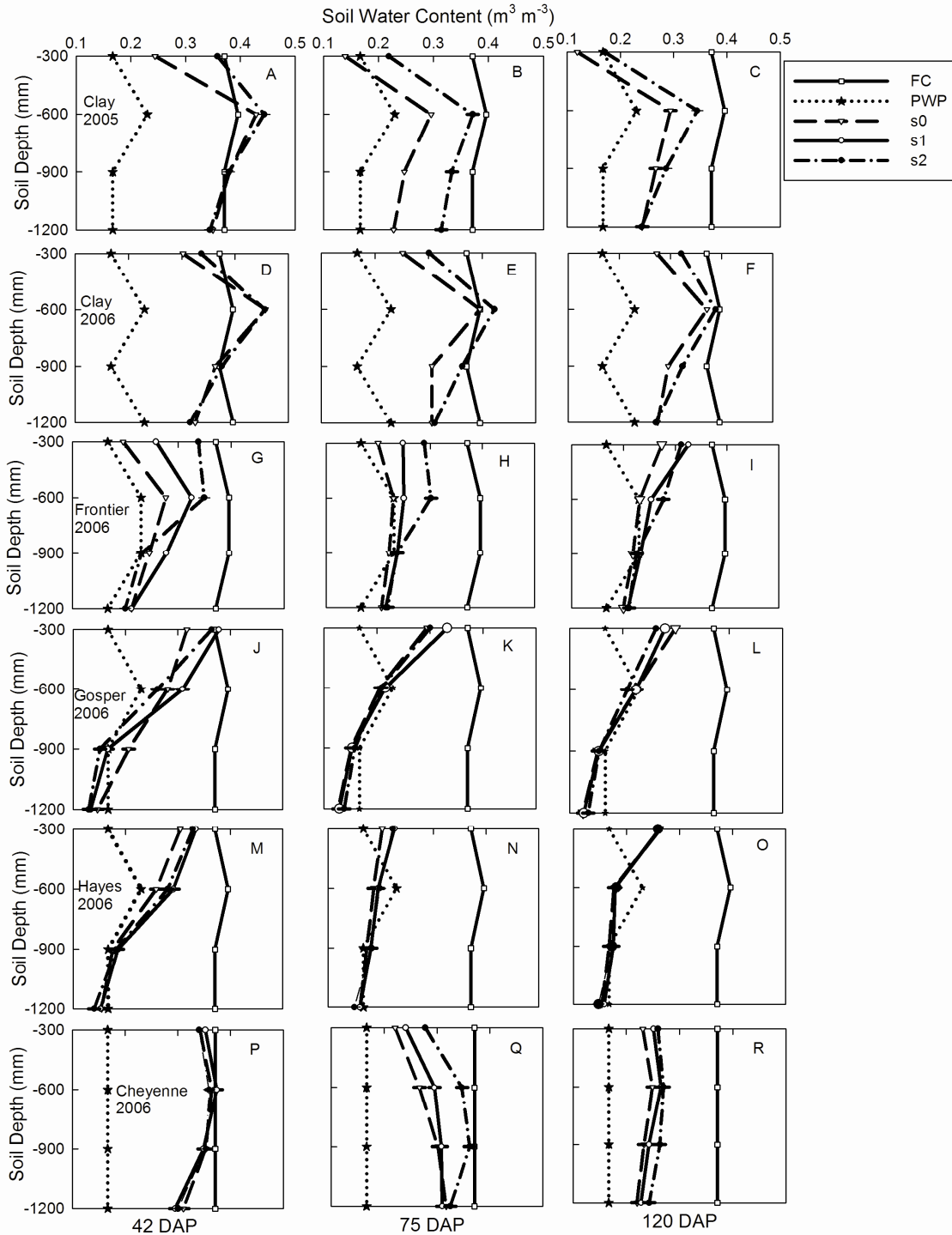


Figure 3. Water content of the soil profile with three row configurations for six site-years in Nebraska in 2005 and 2006 at 42, 75 and 120 days after planting (DAP). s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternated with two rows skipped. FC = field capacity, PWP = permanent wilting point. X-bars = LSD_{0.05}. If X-bars are not present, there are no significant differences among treatments.

panicles m⁻² compared with the high population, subjecting both populations to similar soil water demand (Larson and Vanderlip, 1994; Conley et al., 2005; Bandaru et al., 2006). Evaporation can be a major

concern in skip-row planting but residue cover in the inter-row area and no-tillage minimizes evaporative loss of stored soil water for the benefit of crop use (Routley et al., 2006).

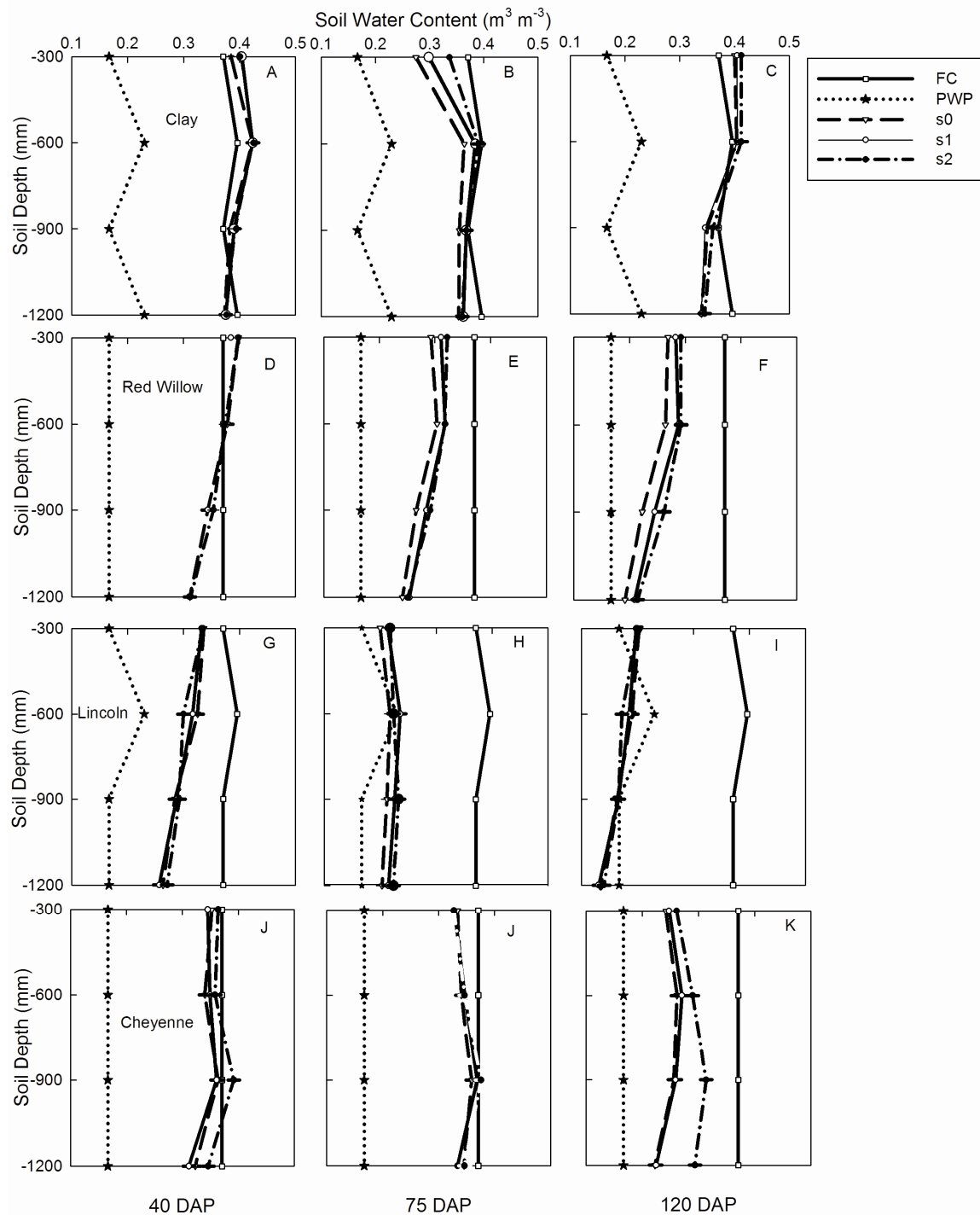


Figure 4. Soil water content in the soil profile under three row configurations at 40, 75 and 120 days after planting (DAP) at four site-years in Nebraska in 2007. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternated with two rows skipped. FC = field capacity, PWP = permanent wilting point. X-bars = $LSD_{0.05}$. If X-bars are not present, there are no significant differences among treatments.

Grain yield

Grain yield results are reported in detail by Abunyewa et al. (2010) and the effects of row configuration on grain

yield are summarized here. Grain yield was greater with s0 at the Clay County site in all three years compared with skip-row planting (Figure 5). This agrees with other findings that yield potential can be reduced in high

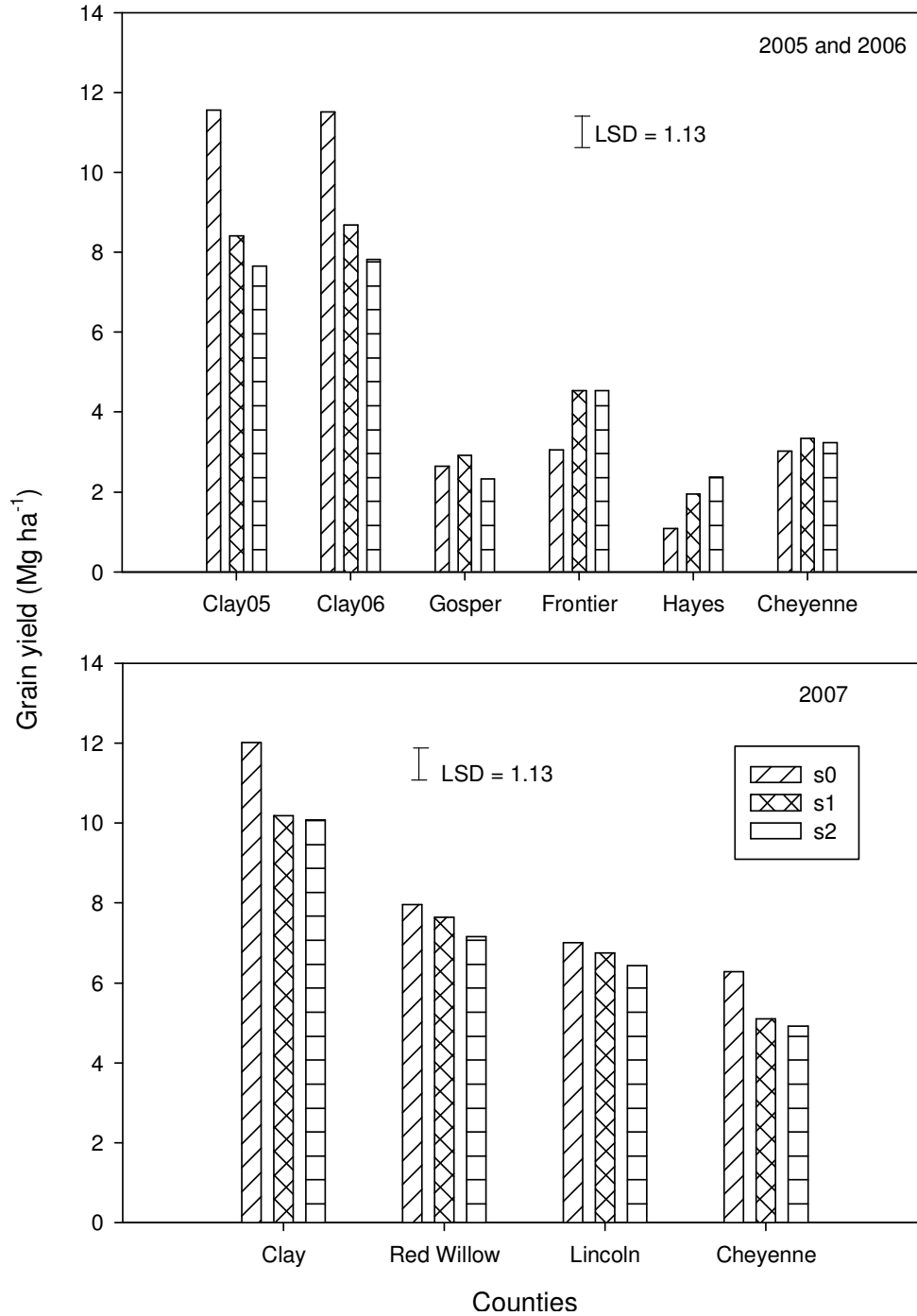


Figure 5. Effects of row configuration on grain sorghum yield from 2005 to 2007 in Nebraska. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternated with two rows skipped. Y-bars = LSD_{0.05} appropriate for the site.

yielding environments when using wider rows due to the inability of the plants to efficiently utilize available resources (Holland and McNamara, 1982). With adequate SWC due to higher growing-season rainfall at Clay County in all three years and at all sites in 2007, uniform stands and narrow spacing produced greater grain yield compared with skip-row configuration.

At the Gosper, Lincoln and Red Willow County sites, considered moderate rainfall locations, grain yield with skip-row planting was equal to s0 (Figure 5). Water availability at critical growth stages is often more important than total precipitation (Lafarge et al., 2002) and water deficits at flowering and grain fill stages can severely reduce grain sorghum yield (Maman et al., 2003,

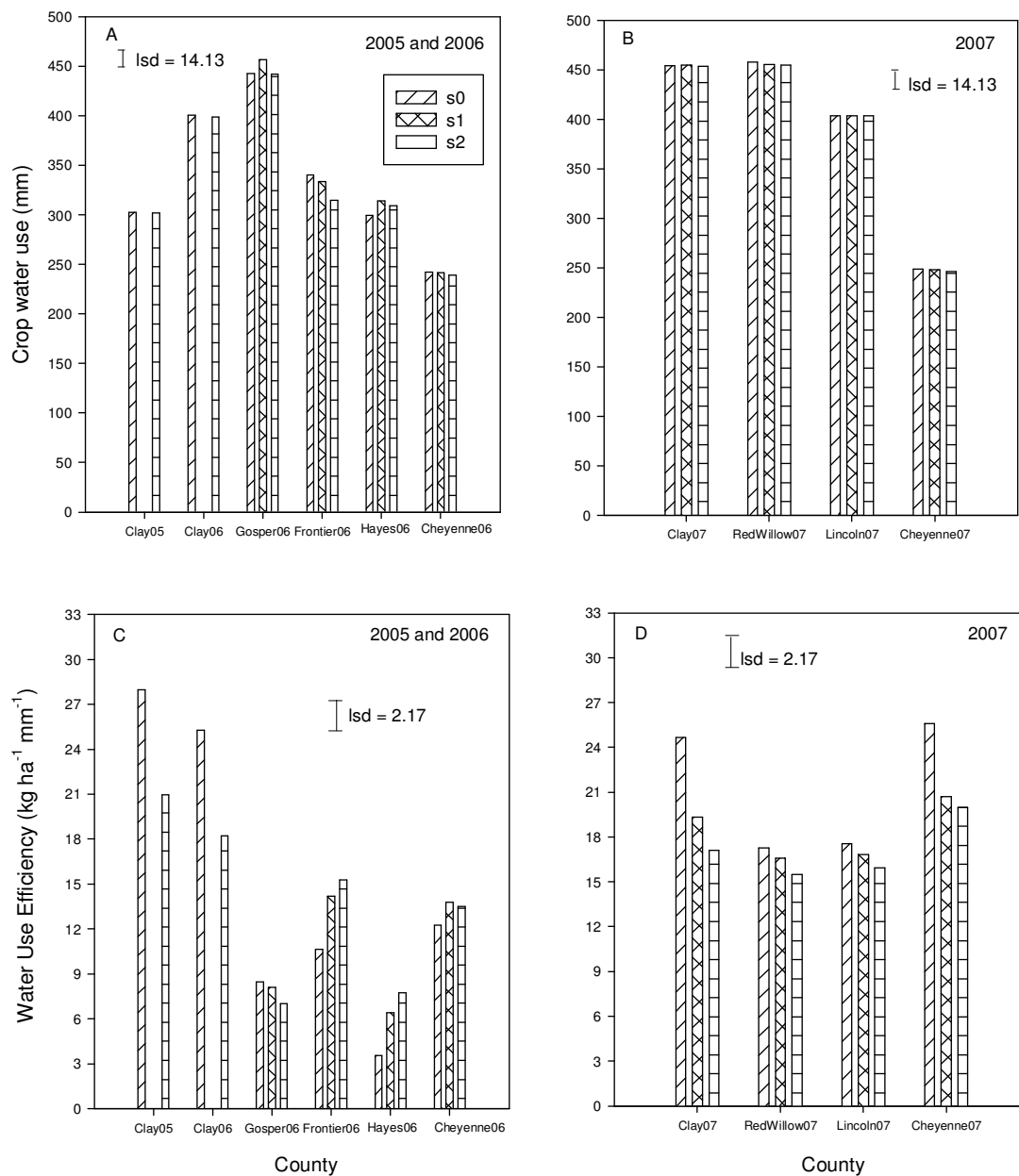


Figure 6. Effect of three row configurations on crop water use (A and B) and water use efficiency (C and D) of grain sorghum at physiological maturity across Nebraska. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternated with two rows skipped. Y-bars = $LSD_{0.05}$ within site-year.

2004). With high growing-season precipitation in 2007, grain yield with s0 was generally higher than with s2 at all sites. At the Hayes and Frontier County sites in 2006, skip-row configurations produced 5 to 123% (0.3 to 1.4 $mg\ ha^{-1}$) higher grain yield than s0, with a trend for higher grain yield with skip row configuration at Cheyenne County in 2006 (Figure 5). These results confirm findings of other studies that showed the grain yield advantage of skip-row planting of grain sorghum over conventional planting, under water deficit conditions (Holland and

McNamara, 1982; Routley et al., 2003; Collins et al., 2006).

Crop water use and water use efficiency at physiological maturity

Crop water use ranged from a site mean of 242 mm at the Cheyenne County site in 2007 to 458 mm at the Red Willow County site in 2007 (Figure 6). At anthesis, CWU

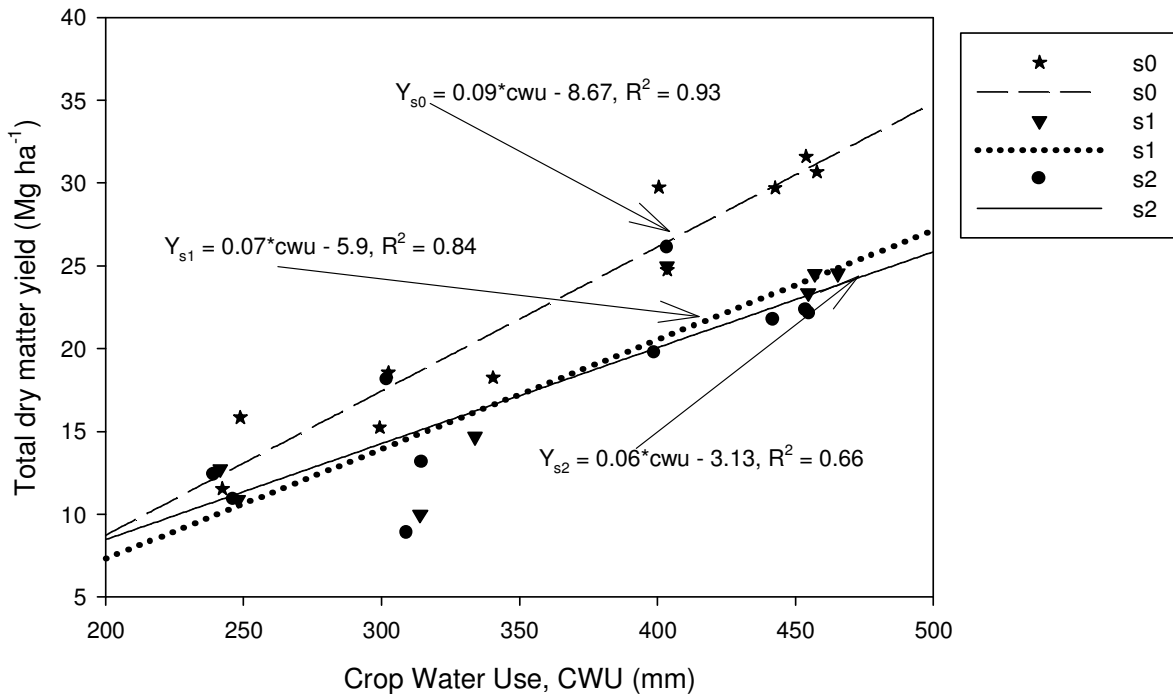


Figure 7. Relationship between crop water use (CWU) and total crop yield at physiological maturity with three row configurations across 10 site-years in Nebraska from 2005 to 2007. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternated with two rows skipped.

was higher with s0 than with skip-row planting for all site-years. However, as the season and water depletion progressed, CWU with skip-row planting increased with use of the plant-available water in the inter-row area and was not different from s0 planting at physiological maturity except at the Frontier and Hayes County sites (Figure 6). The difference in CWU at physiological maturity was $s0 > s1 > s2$ at Frontier County and $s1 > s0 = s2$ at the Hayes County site. Maximum grain yield did not correspond with maximum CWU across site-years as CWU was dependent on rainfall events and other weather factors of the site. Routley et al. (2003) observed higher CWU of grain sorghum with s0, compared with skip-row planting at anthesis, but there were no differences in CWU between s0, s1 and s2 at maturity.

Row configuration x plant population interactions did not significantly influence WUE at any of the 10 site-years. Water use efficiency with s0 across site-years ranged from 3.6 at the Hayes County site to 27.9 kg ha⁻¹ mm⁻¹ at the Clay County site in 2005 (Figure 6). With skip-row configurations, WUE ranged from 6.4 at Hayes to 20.7 kg ha⁻¹ mm⁻¹ at Cheyenne County with s1 in 2007, and from 7.0 at Gosper to 20.9 kg ha⁻¹ mm⁻¹ at Clay County with s2 in 2005. Water use efficiency was highest with the s1 and s2 compared with the s0 configuration at site-years with mean growing-season precipitation < 2 mm day⁻¹ (low rainfall site-years) and lower at site-years where the mean growing-season precipitation was > 2.5 mm day⁻¹ (high rainfall site-years). At the Clay County site,

WUE was higher with s0 in all years compared with skip-row planting. Water use efficiency was similar for s1 compared with s2 for all site-years except Cheyenne County in 2006 and Clay County in 2007. Improvement in WUE in water deficit environments with skip-row configuration can be attributed to the increased availability of soil water in the inter-row area at reproductive stages, which was subsequently utilized to increase grain yield.

The linear relationship between CWU and total dry matter yield (stover plus grain) at harvest was steeper with s0 compared with skip-row planting (Figure 7). At lower CWU, differences in total dry yield with s0 compared with skip-row planting were not apparent, but as CWU increased, the rate of dry matter yield increased significantly with s0 planting. At site with higher CWU, wider spacing skip-row configuration is likely to under-utilize solar radiation and soil nutrients compared with s0. The weak linear relationship for s2 suggests that plant-available water was not limited to crop growth at site-years with greater precipitation. Using data of research conducted in the central Great Plains from 1973 to 2004, Stone and Schlegel (2006) observed a linear association between sorghum grain yield and soil water supply (soil water at emergence plus growing-season precipitation). Thus, skip-row configurations can be expected to result in lower yields than conventional planting if the growing season CWU is more than 300 mm. However, distribution of in-season precipitation, vapor pressure deficit, solar

radiation, and wind speed will have significant influences on total yield (Maman et al., 2003; Olufayo et al., 1996).

Conclusions

The initial SWC and the amount and distribution of growing-season precipitation affected CWU and WUE of grain sorghum across site-years. There was less CWU with skip-row compared to s0 planting during vegetative stages with more water availability for reproductive growth with skip-row treatment. This saved water was efficiently converted to grain yield only where soil water deficits were severe. At moderate soil water deficit, grain yield and WUE with skip-row and s0 configurations were similar. Skip-row planting of sorghum grain is recommended where severe growing season soil water deficits are likely to occur, as in western Nebraska.

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