Efficient Utilization of Water and Nitrogen Resources for Grain Sorghum under Rainfed Conditions

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By

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Efficient Utilization of Water and Nitrogen Resources for Grain Sorghum Under Rainfed Conditions

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Grain sorghum (*Sorghum bicolor* L. Moench) is the fifth world leading cereal after maize, wheat, rice and barley. The crop can yield reasonably well under adverse conditions of low soil water and high temperature. A three year field study was conducted in a transect across Nebraska where annual mean precipitation ranges from 300 to 900 mm yr^{-1} to evaluate management practices to optimize yield potential under water limiting conditions. Loss in grain yield due to planting configurations ranged from 20 to 30% with skip-row configurations compared to conventional planting configuration (s0) at the site with greatest precipitation. At a site with moderate precipitation, grain yield was reduced by 18% with plant two skip two configurations (s2) and was not significantly affected with plant one skip one configuration (s1). At sites with the lowest precipitation and significant soil water deficits, grain yield increased with s1 and s2 ranging between 5 and 123% over s0. Considering yield across all sites, s0 yield was greater than skip-row configurations when average yield was above 4.5 Mg ha^{-1}. Water use efficiency was highest with skip-row configuration at low to medium in-season precipitation sites but lower at sites where the mean in-season daily precipitation was greater than 2.5 mm. Increased N rate resulted in increased grain yield with s0 but there were no significant response to N application after 100 kg N ha^{-1}. With skip-row planting,

raising N rate above 50 kg N ha^{-1} did not significantly increase grain yield. Conventional planting (s0) had significantly higher agronomic N use efficiency (AE_N) and partial factor productivity of N applied (PFP_N) than skip-row configurations. Water and nitrogen stress both resulted in significant increase of leaf and canopy reflectance. A model calibrated in a greenhouse study using a reciprocal index in the green and red edge and in the NIR ranges predicted chlorophyll content with RMSE ranging between 52 and 56 mg m^{-2}.

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TO GOD BE THE GLORY

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CHAPTER ONE

GRAIN SORGHUM PRODUCTION, IMPORTANCE AND CHALLENGES.

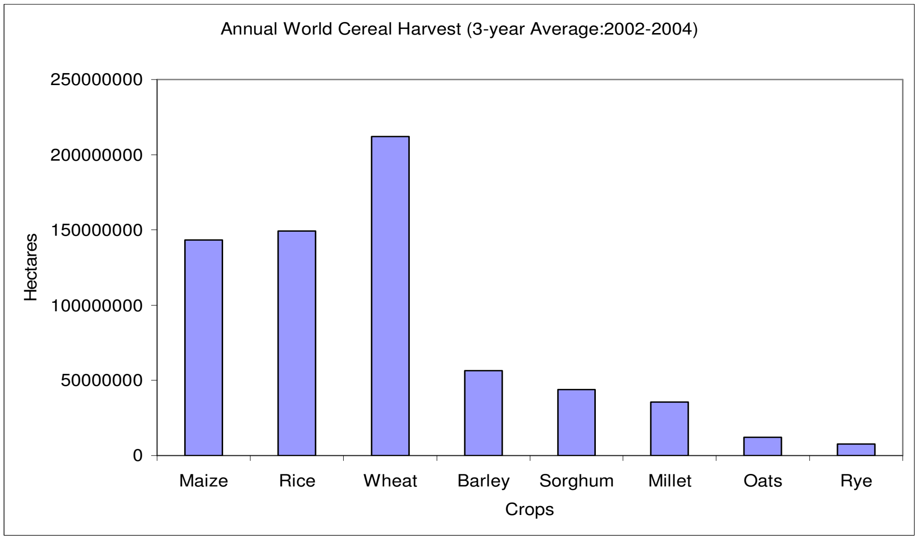
1.1 Crop description and production

Sorghum (*Sorghum bicolor* (L.) Moench) is known under a variety of names: great millet and guinea corn in West Africa, kafir corn in South Africa, dura in Sudan, mtama in eastern Africa, jowar in India and kaoliang in China (Purseglove, 1972). In the USA grain sorghum is usually referred to as milo.

Sorghum belongs to the tribe Andropogonae of the grass family *Poaceae* (FAO, 1991). As with maize, sorghum uses the C4 malate cycle, the most efficient form of photosynthesis and has greater water use efficiency than C3 plants. Sorghum may well offer the best opportunity to satisfy the doubling demand in the developing world by 2020, as a food for the poor and an alternative feed and food to maize (Harlan and de Wet, 1972; Maunder, 2005). Sorghum uniquely adapts to environmental extremes of abiotic stress making this crop the logical grain to support a world predicted to have 25% of its population experiencing severe water scarcity by 2025.

Grain sorghum is the third most important cereal crop grown in the USA and the fifth most important cereal crop grown in the world (Fig. 1.1). The USA is the world's largest producer of grain sorghum followed by India and Nigeria. It is a leading cereal grain produced in Africa and is an important food source in India. The leading exporters of grain sorghum are the USA, Australia and Argentina (Grain Council, 2008). The grain constitutes the main food for over 750 million people who live in the semi-arid tropics of

Africa, Asia, and Latin America, and globally over half of all sorghum is used for human consumption (FAO. 2007; National Sorghum Producers. 2006).



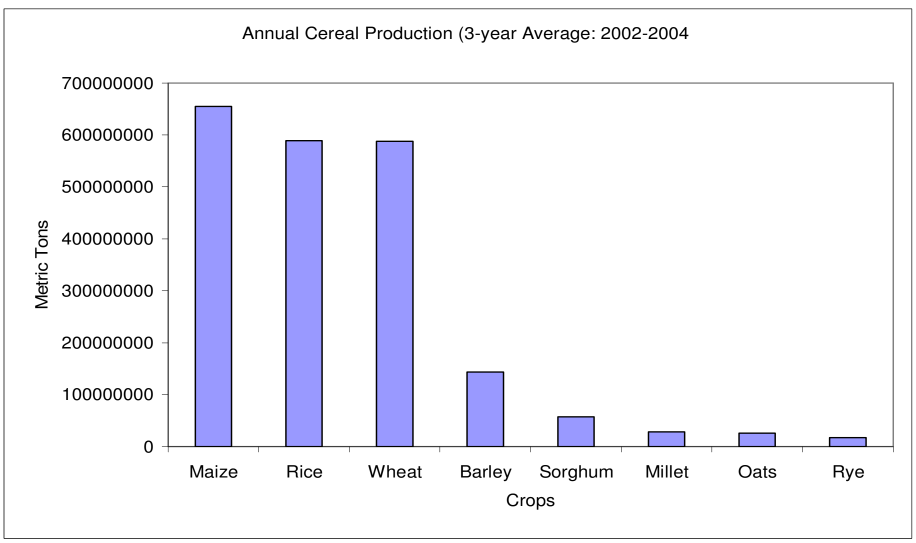


Figure 1.1. World Annual Cereal Production (in hectares) and harvest (in metric tons). Statistics are from FAOSTAT 2005, Last modified October 16, 2008.

1.2 Importance and uses

In many parts of the world sorghum has traditionally been used in food products and in various food items: porridge, unleavened bread, cookies, cakes, and malted beverages are made from the grain. It is also an important animal feed used in countries like the USA, Mexico, South America and Australia. In West Africa and many developing countries, the stalk is use as fencing and roofing material, ruminant animal feed, and as a source of fuel energy for cooking. Sorghum prices are likely to increase due to huge increase in worldwide grain demand from ethanol plants. According to Roe and Jolly (2006), high profits from ethanol is stimulating the building of ethanol plants and a continuing increase in grain being consumed for fuel rather than livestock feed. Ethanol production in the USA has already increased the price of grain, which may go higher over the next few years. Higher prices will stimulate increased production of sorghum (Grains Council, 2008).

1.3 Grain sorghum growth and development

Vanderlip (1993) has described grain sorghum growth and development and has assigned numbers from zero to nine similar to the numbering system used in corn. Time required to each growth stage, Stage 0- emergence to Stage 9-physiological maturity depends both on the hybrid and the environmental factors such as soil fertility, water, climatic conditions and management practices.

The crop grows well on most soils but better in light to medium textured soils. The soil should preferably be well-aerated and well-drained with pH values ranging from

5 to 8.5 (Fageria et al., 1991). Sorghum is moderately tolerant to short periods of water-logging and salinity (Carter et al., 1989; Maas et al., 1986).

1.4 Drought and temperature tolerance

Sorghum is more tolerant to high temperature (> 38 ^{o}C) and drought than most major agronomic crops. Grain sorghum requires less water than corn, under low to modest yield conditions and is an alternative to corn in production environments with frequent severe water deficits (Bennett et al., 1990; Maman et al., 2004; Carter et al. 1989; AFRIS-FAO, 2006; Wikipidia, 2006). The crop can grow where available water is less than 500 mm and can respond positively to higher precipitation (Fribourg, 1995). Sorghum can reduce its water losses by its heavy wax cuticle, curling of its leaves and relatively small number of leaf stomata (Gardner et al. 1981). When water supply is limiting, sorghum has more efficient water transport system than corn or cotton (Ackerson and Krieg, 1977). Sorghum a has fibrous root system that grows rapidly in deep soils and it is efficient as water forager. The adventitious root starts several weeks after emergence and extends rapidly up to 2m, depending on depth of soil wetting (Sullivan and Blum, 1970).

1.5 Water use and water use efficiency

Graser (1985) compiled seasonal water use of sorghum at several locations from 1976 to 1981 and reported a range of 179 to 540 mm under dryland and 321 to 645 mm under irrigated conditions. Erie et al. (1981) reported that consumptive water use increases with plant growth, reaches a peak and decreases by harvest time. Water use of sorghum was found to be greatest during the boot and soft dough stage and lower during

seedling, tillering and ripening stages (Porter et al., 1960). Several factors including temperature, precipitation, solar radiation, humidity, wind movement and hybrid affects sorghum water use efficiency. The water use curve in any one year or at any site will vary from long term average due to changes in some of the factors listed above. Water use efficiency ranging from 13 to 29 kg ha^{-1} mm^{-1} has been reported in literature under dryland and irrigated condition (Savikumar et al., 1979; Hedge et al., 1976; Salinas-Garcia, 1981; Porter et al., 1960).

1.6 Row spacing and skip-row configuration

With adequate water, narrow row spacing will produce higher grain yield than wide row spacing and skip-row configuration. Wide row and skip-row planting are based on the assumption that in a water deficit environment, soil water stored early in the season in the skipped area will be utilized and thus enable the planted rows to have a yield advantage over planting in contiguous narrow rows. With wider row and skip-row planting, the inter-row spacing increases as the intra-row space decreases when constant plant population is maintained. The inter-row and intra-row spacing affects the degree of competition for water, light and nutrients.

Since the 1960's several studies on the effect of different row spacing on grain sorghum yield has been carried out under both irrigated and dryland conditions. Many of these studies reported that under adequate soil water conditions narrow row spacing had greater yield than wide row spacing (Porter et al., 1960; Stickler and Wearden, 1965; Thomas et al. 1981, Bishnoi et al., 1990). Bandaru et al. (2006) reported that grain sorghum planted in clumps had a grain yield advantage over uniform plant stand in

environments with yield potential of up to 3 Mg ha^{-1}, but clump stand had lower yield than uniform plant stand. They reported that clumps had fewer tillers, less biomass production and stored soil water used during the reproductive stage for increased grain yield. Optimum row spacing depends on soil water availability and yield potential and soil fertility (Porter et al., 1960; Thomas et al., 1981; Collins et al., 2006). It has been reported that at a high yield site, an increase in row spacing reduced grain yield and increased weed incidence, and at low yield site, increase row spacing increased grain yield (Holland and McNamara, 1982; Staggenborg et al., 1999).

Due to earlier canopy closure and greater ground cover, narrow row spacing has higher light interception than wide row and skip-row planting, increasing photosynthesis for growth and storage (Adams et al., 1978; Steiner, 1986; Flenet et al., 1996). Other likely benefits from narrow row spacing due to early canopy cover includes decreased soil erosion, decreased runoff, increased infiltration, and decreased wind-induced lodging (Atkins and Martinez, 1971). Narrow spacing will usually increase produced greater yields in eastern Nebraska unless water is limiting (Villa et al., 1988).

With wide row spacing, more solar radiation in the inter-row area will raise soil temperature and increase evaporation. On the other hand, the solar radiation intercepted by the closed canopy will increase transpiration. It has been reported that plants in narrow row spacing use more water earlier in the season than those with wide row spacing (Porter et al., 1960; Hedge et al., 1976; Salinas- Garcia, 1981). Some studies have indicated higher water use efficiency in narrow row spacing (Porter et al. 1960, Hedge et al. 1976). However, Brown and Shrader (1959) showed that wide row spacing had higher water use efficiency while Salinas-Garcia (1981) found no difference between the two.

It has been hypothesized that wide row spacing promotes intra-row competition which reduces biomass production and water use in the early stages of growth. Late in the season, more water remains for grain production in the wide row spacing than with the narrow rows where intra-row competition was lesser due to uniform spacing, with higher biomass production and less saved soil water (Brown and Shrader, 1959; Thomas et al. 1981).

1.7 Problem Statement

Sorghum is drought tolerant and therefore commonly grown in semi-arid conditions. Prolonged drought, insufficient season length and severe water deficits during flowering period causing pollination failure are major causes of yield loss (Carter et al. 1989). Skip-row planting is one strategy which has been suggested to use stored soil water more efficiently, improving yield stability and reducing production risk in more marginal cropping areas (McLean et al., 2003; Routley et al., 2003).

1.8 General Hypotheses and Objectives of the study

Soil water conserved in the inter-row area during the early stages of crop growth can be utilized during reproductive stages when there is low in-season precipitation. This will reduce the risk of total crop failure due to water stress, improve harvest index and grain yield. There is a need to explore and evaluate the interactions of skip-row planting, plant population and N application. This study evaluated production practices that can make sorghum a more viable alternative crop in western Nebraska (Fig. 1.2), where lack of precipitation during the growing season can severely reduce crop production.

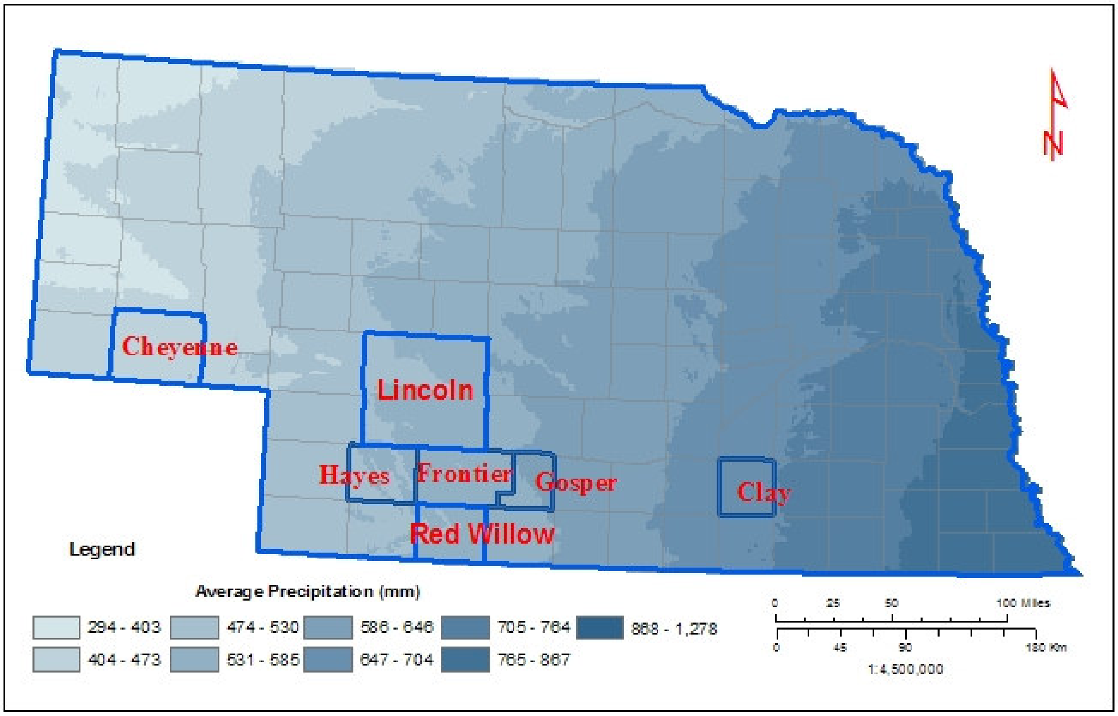


Figure 1.2. Research study sites across Nebraska in 2005, 2006 and 2007

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CHAPTER TWO

SKIP-ROW CONFIGURATION AND PLANT POPULATION EFFECTS ON SORGHUM GRAIN YIELD AND YIELD COMPONENTS.

2.1 Abstract

Conventional row planting of grain sorghum typically results in the highest grain yield when soil water is adequate throughout the season, but skip-row planting may be a means to conserve soil water so that water deficits are reduced during reproductive growth. A three-year field study was conducted to evaluate the effect of skip-row configuration and plant population on grain yield and yield components in a transect across Nebraska where annual mean precipitation ranges from 300 to 900 mm yr^{-1}. Three row configurations including all rows planted (s0) at 76 cm, alternate rows planted (s1), and two rows planted alternated with two skipped rows (s2) were evaluated in a complete factorial with two plant populations. Soil water was measured to 1200 mm depth biweekly with a neutron probe. In all three years, loss in grain yield due to skip configuration ranged from 20 to 30% with s1 and s2 compared to s0 at the site with greatest precipitation. At a site with moderate precipitation, grain yield was reduced by 18% with s2 but was not different with s1. At sites with lowest precipitation and larger soil water deficits, grain yield increased with s1 and s2 ranging between 5 and 123% over s0 in 2006. Considering yield across all sites, there was a crossover at about 4.5 Mg ha^{-1} with s0 outperforming skip-row configurations when mean yield was above 4.5 Mg ha^{-1}. The threshold of soil water content for grain was lower with skip-row configurations than with s0. The relationship between total in-season available water and grain yield was

logarithmic with a coefficient of determination of 88% with s0 and 81% with skip-row configurations. Above 680 mm in-season total water (stored soil water plus precipitation), s0 configuration had higher grain yield mm^{-1} of water than skip-row configurations.

2.2 Introduction

Dryland grain sorghum is a major crop produced in the more marginal (<600 mm annual rainfall) cropping areas primarily in the central and southern Great Plains of the United States (Carter et al., 1989). The crop has the ability to delay development under water stress during the vegetative growth stages and resume growth when water conditions improve. This drought avoidance mechanism works well under tropical and subtropical conditions with a long growing period. However, this mechanism of drought resistance may result in poor yield due to prolonged drought, insufficient season length or when it occurs at critical growth stage.

Skip-row planting is one strategy which has been suggested to use stored soil water more efficiently, improving yield stability and reducing production risk in more marginal cropping areas (McLean et al., 2003; Routley et al., 2003). The strategy is based on the rationale that the suppression of early plant growth is likely to improve water use efficiency of dryland grain sorghum grown on stored soil water in promoting plant competition by changing the arrangement of plants in the field (Blum and Naveh, 1976).
Early plant competition could be increased by maintaining plant population on an area basis but increasing the row spacing. This will reduce dry matter and water use with the

benefit of the saved water in the skipped area for use by the plant during flowering and grain fill.

In seasons with low rainfall, soil water reserves are often depleted in conventional planting by the time of crop flowering and low yield or total crop failure can result. With skip-row planting, the soil water conserved in the inter-row area during the early stages of crop growth can be utilized during reproductive stages when there is low in-season precipitation. This may reduce the risk of total crop failure due to soil water deficits, improve harvest index and increase grain yield.

Skip-row planting is expected to be most effective where soil has high water holding capacity and soil water is adequate for the crop to reach the early reproductive stage without significant water deficit stress, as stored soil water will be available for use during flowering and grain filling. In growing conditions with more favorable soil water, skip-row yields are likely to be less than conventional planting yields as solar radiation, nutrients and water in the unplanted area may not be fully utilized. Depending on the timing and severity of stress, yield components, including grain size, grains per panicle and panicle number may be affected with an ultimate effect on harvest index (Thomas et al., 1981).

According to Evans and Wardlaw (1976), number of panicles m^{-2} and number of kernels per panicle are determined early in plants life cycle and are influenced by environmental factors such as temperature and water. For grain sorghum, potential kernel number is set during the reproductive and kernel weight during the grain fill period (Eastin et al., 1999). Water stress at reproductive stage will affect number of kernels irreversibly and adequate soil water after this growth stage will have limited increase in

kernel weight. Several factors including uniformity of plant stand, border effect, N application, row spacing and plant population, delayed planting, soil water differences, weed competition and defoliation have been shown to affect yield components in grain sorghum (Larson and Vanderlip, 1994; Stickler and Wearden, 1965; M'Khaitir and Vanderlip, 1992; Norwood, 1992; Rajewski et al., 1991). Water stress at various growth stages has been associated with particular yield components: panicles m^{-2} for pre-flower (Mahalakshmi and Bidinger, 1986); kernels per panicle for mid-season water stress (Bidinger et al., 1987), weed competition (Limon-Ortega et al., 1998), and kernel weight for terminal water stress (Bidinger et al. 1987).

Although Myers and Foale (1981) failed to established an optimum population in repeated row spacing and population studies, other studies reported various optimum plant populations ranging between 50000 and 100000 plants ha^{-1} under dryland conditions (Thomas et al., 1980; 1981, Wade and Douglas, 1990). Staggenborg et al. (1999) suggested 123,500 and 185,250 plants ha^{-1} for early to medium season grain sorghum hybrids in Kansas when the subsoil water is adequate. The optimum plant population range for grain yield is wide in crops with a large capacity to produce tillers, and seeding rate should be guided by subsoil water status and hybrid maturity. Since sorghum has the capacity to tiller, lower populations compensate by having more tillers than high populations. Different strategies such as reduced seeding rate, row spacing and skip-row planting have been used to improve soil water availability later into the growing season (Blum and Naveh, 1976; Larson and Vanderlip, 1994).

2.3 Hypothesis and objectives

The hypothesis for this study was that changing plant population and row spacing could have different but interacting effects on the use of available resources that will influence grain yield and yield components. The general objective of this study was to determine planting practices to improve grain sorghum productivity in western Nebraska where inadequate precipitation often severely reduces rainfed crop yield.

The specific objectives of the study were to:

i. Quantify the effect of row configuration on biomass, grain yield and yield components.

ii. Evaluate the interactions of skip-row planting and plant population on grain sorghum production.

2.4 Materials and Methods

From 2005 to 2007, field studies were conducted at different locations across southern Nebraska (Fig. 1.2) to evaluate the effect of skip-row configuration and plant population of grain sorghum on grain yield and yield components. All fields were no-tilled and non-irrigated. Table 2.1 lists soil series and their taxonomic classes of the 10 site-years and some agronomic practices used. Three planting configurations and two plant populations were evaluated in a complete factorial design laid out in a randomized complete block design with four replications at all site-years. The row configurations included all rows planted or conventional planting (s0), with base 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).

At Clay County, a relatively high rainfall site with annual mean precipitation of 734 mm (Fig. 1.2), seeding rate and thinning was done after emergence to obtain 75,000 and 150,000 plants ha^{-1}. At the remaining six county sites (Gosper, Frontier, Hayes Center, Lincoln, Red Willow and Cheyenne) with low to moderate rainfall, annual mean precipitation ranging from 400 to 600 mm, seeding rate and thinning was done after emergence to obtain 50,000 and 100,000 plants ha^{-1}. Medium (110 days) maturing grain sorghum cv. Dekalb 42-20 was planted at the Clay Co. site and early (105 days) maturing Dekalb 29-28 (Monsanto, Denver, Colorado., USA) was planted at the Red Willow, Lincoln, Gosper, Frontier, Hayes and Cheyenne Co. sites. Plant population remained constant across all treatments, resulting in a higher within-row population in skip-row treatments. Fertilizer application was based on the University of Nebraska recommendation for the crop and soil nutrient content before planting at each site (Ferguson, 2000). Gosper, Frontier, Hayes and Red Willow Co. sites were on cooperating producer's fields while Clay, Lincoln and Cheyenne Co. sites were located on research stations. Herbicides were applied by the producer according to the weed control program for the field.

To measure volumetric soil water content at each site, neutron probe access tubes were installed in the center of the skipped area of s1 and s2 configurations and in the center between two rows of s0 configuration. Volumetric soil water content was measured beginning three weeks after planting at two or three weeks interval until physiological maturity, using a neutron probe (Troxler 4301, Troxler Electronic Labs. Research Triangle Park, NC, USA) at depths of 300, 600, 900, 1200 mm. In-season

precipitation, and long term (50-year) average in-season precipitation data were collected from nearest Automated Weather Data Network.

Above ground biomass at anthesis and physiological maturity were harvested from an area of 2.28 m^2, oven dried at 65°C for 72 hours and weighed. Grain yield was determined from 60.8 m^2 at the Clay Co. site and from 30.4 m^2 at the remaining sites of harvested area and standardized at 135 g kg^{-1} water content. Stover weight, grain weight per panicle, 100 kernel weight, number of kernels per panicle, number of panicles and harvest index were determined with harvested above-ground sorghum from an area of 2.28 m^2. Plant samples were oven dried at 65°C for 72 hours and weighed. Panicles were mechanically threshed and grain yield was standardized at 135 g kg^{-1} water content.

2.5 Statistical analysis:

All data were analyzed by using analysis of variance mixed linear model procedure (Proc Mixed, SAS Institute, 2007, Cary, NC, USA). The format of the ANOVA was a randomized complete block design with four replications.

Test of homogeneity of variances (Hartley, 1950) across sites showed that variances were heterogeneous. Each site-year data was therefore analyzed separately. When an F test was significant at $P \leq 0.05$, the least significant difference (Fisher's protected LSD) at $P \leq 0.05$ was calculated and used to separate treatment means. Regression analysis was performed to establish the relationship of chlorophyll content with sorghum leaf N concentration at anthesis, and grain yield at physiological maturity.

Table 2.1. Soil series, taxonomic classes, agronomic data and rainfall at each study site.

	County						
Site, soil and agronomic data	Clay	Gosper	Frontier	Hayes	Cheyenne	Red Willow	Lincoln
Location	lat.40°34'N; long.98°08W; 543.3 m elev	lat.40°28'N; long.99°53W; 732 m elev	lat.40°40'N; long.100°29W; 829 m elev	lat.40°30'N; long.101°01W; 922.0 m elev	Lat. 41°12'N; 103°01'W; 1317 m elev.	Lat. 40°23'N 100°58'W; 792 m elev.	Lat. 41°05'N; 100°75'W; 922 m elev.
Soil series	Crete silt loam	Holdrege silt loam	Hall silt loam	Kuma silt loam	Duroc loam	Holdrege & Keith silt loam	Holdrege silt loam
Taxonomic class	fine, smectitic, mesic Pachic Arguistolls	Fine-silty, mixed, superactive, mesic Typic Argiustolls	Fine-silty, mixed, superactive, mesic Pachic Arguistolls	Fine-silty, mixed, superactive, mesic Pachic Arguistolls	Fine-silty, mixed, superactive, mesic Pachic Haplustolls	Fine-silty, mixed, superactive, mesic Typic/Aridic Argiustolls	Fine-silty, mixed, superactive, mesic Typic Argiustolls
Previous crop	Corn	Corn	Corn	Corn	Wheat, Corn	Corn	Corn
Variety	Dekalb 42-20	Dekalb 29-28	Dekalb 29-28	Dekalb 29-28	Dekalb 29-28	Dekalb 29-28	Dekalb 29-28
Plant Pop	75,000/ha 150,000/ha	50,000/ha 100,000/ha	50,000/ha 100,000/ha	50,000/ha 100,000/ha	50,000/ha 100,000/ha	50,000/ha 100,000/ha	50,000/ha 100,000/ha
Plant date	May 24, 2005	May 16, 2006	May 23, 2006	May 24, 2006	June 1, 2006	May 24, 2007	Jun. 1, 2007
Harvest date	Oct. 14, 2005	Oct. 31, 2006	Oct. 31, 2006	Nov. 1, 2006	Oct. 17, 2006	Oct. 2, 2007	Oct. 2, 2007
Plant date	June 7, 2006				June, 2007		
Harvest date	Oct. 25, 2006				Oct. 3, 2007		
Plant date	June 6, 2007						
Harvest date	Oct. 10, 2007						

2.6 Results and Discussion

2.6.1 In-season precipitation across sites

Monthly in-season precipitation at the Clay Co. site in 2005 followed the general pattern of distribution as the 50-year average but had only 71% of the total average in-season precipitation (Fig. 2.1A). Total monthly rainfall ranged between 40 and 77 mm with the highest precipitation in June. The highest in-season precipitation at the Clay Co. site in 2006 (Fig. 2.1B) was observed in August (118 mm) followed by July (83 mm) and September (75 mm).

In-season precipitation in 2006 was 82% of the 50-year average and was higher than the in-season precipitation observed in 2005. The wettest year at Clay Co. was 2007 with minimum precipitation of 40 mm occurring in September and maximum of 144 mm in October (Fig. 2.1C). The 2007 season started with high precipitation (120 mm) in May and the second highest rainfall event in the season in August. The 2007 season had 120% of the 50-year average precipitation over the growing season.

The total in-season precipitation in 2006 was 496 mm at Gosper, 390 mm at Frontier, 376 mm at Hayes, and 261 mm at Cheyenne Co. sites (Figs. 2.1D, F, H and J). These represented 119% for Gosper, 87% for Frontier, 100% for Hayes, and 82% for Cheyenne Co. sites of the 50-year average of in-season precipitation. Most of the 2006 in-season precipitation at Gosper Co. occurred in August and September, more than 70 days after sowing (DAP). In 2007, all sites except Cheyenne Co. had above-average precipitation over the same period of time. Compared with annual mean precipitation during the season, precipitation was 77% at Cheyenne Co., 109% at Lincoln Co. and 121% at Red Willow Co. with 261 mm, 377 mm and 388 mm, respectively.

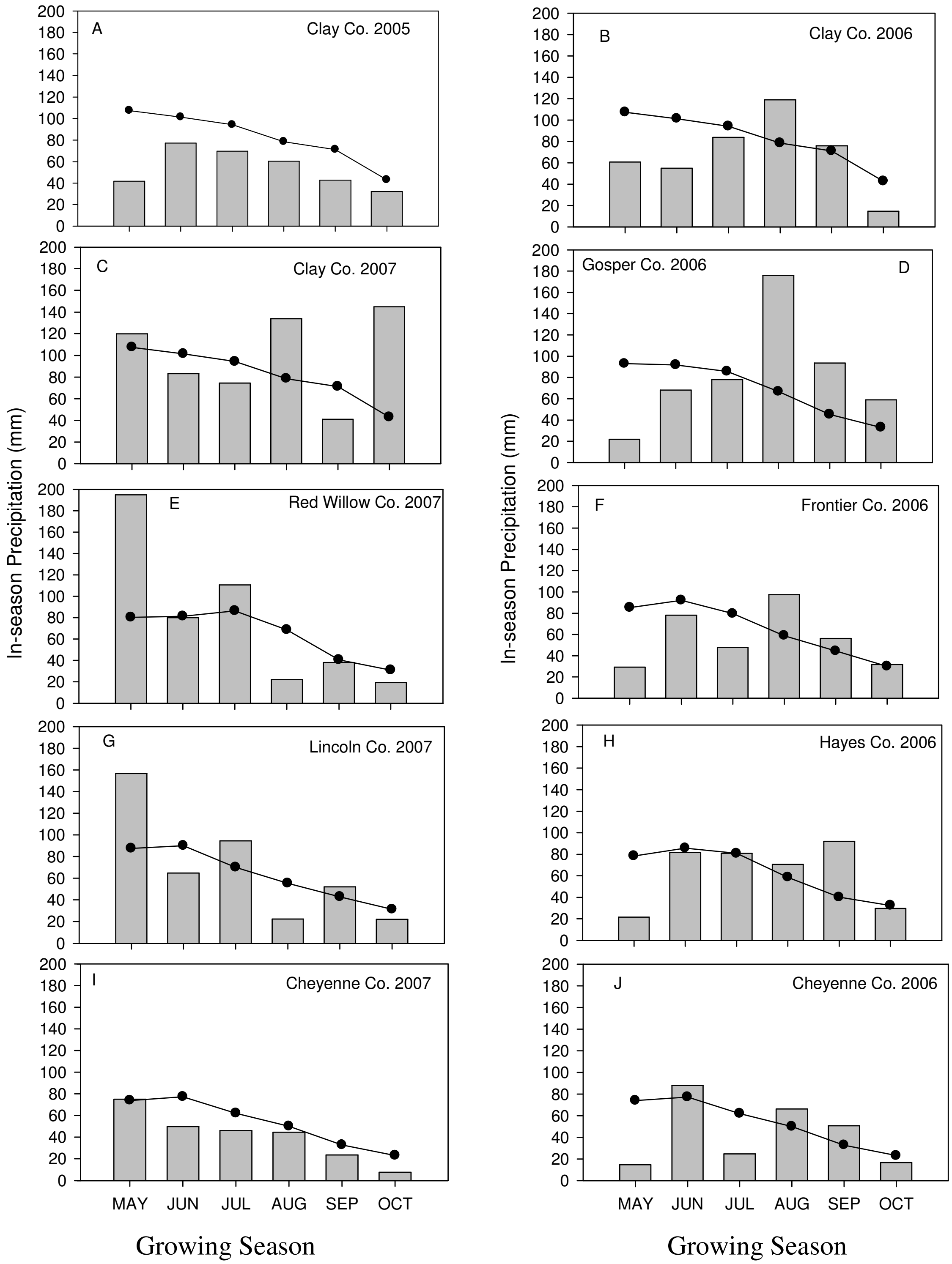

Figure 2.1. In-season precipitation monthly total (bars) and 50-year mean (line) at all county sites in 2005, 2006, 2007.

2.6.2 Biomass and stover yield

The row configuration x plant population interaction effects were present at the Clay Co. in 2005, Gosper in 2006, Lincoln and Red Willow Co. sites in 2007 (Table 2.2). The effect of plant population on biomass yield at anthesis was not consistent across site-years. The higher population with s0 configuration at the Clay, Lincoln and Red Willow Co. sites had higher biomass yield compared with the low plant population (Fig. 2.2). The reverse was observed at the Gosper Co. site where lower population produced greater biomass with s0. At the Gosper, Lincoln and Red Willow Co. sites the differences in biomass yield between the two plant populations with skip-row configurations were not significant. At the Clay Co site in 2005, higher plant population with s1 out-yielded s1 with lower population.

At all site-years, biomass yield with s0 at anthesis was significantly higher than that with the skip-row configurations (Fig. 2.3). At the Clay and Cheyenne Co. sites in 2006, the s1 treatment had higher biomass yield than the s2. In all three years, sorghum was sown when soil water was adequate to ensure good plant establishment. At each site, initial stored soil water status and in-season precipitation in the early growth stages of growth supported high biomass production with s0 configuration resulting in higher biomass yield compared with skip row configuration treatments.

Table 2.2. Summary of analysis of variance of biomass yield at anthesis (Mg ha^{-1}) of grain sorghum with three row configurations and two seeding rates at ten site-years.

		Clay 2005	Clay 2006	Clay 2007	Gosper 2006	Frontier 2006	Hayes 2006	Cheyenne 2006	Cheyenne 2007	Lincoln 2007	Red Willow 2007
Source	DF	----------	----------	----------	----------	Mean square	----------	----------	----------	----------	----------
Row Config. (RC)	2	93.19**	622**	467**	21.86*	613.9**	69.71*	105.3**	59.91**	449.6**	892**
Plant Pop (PP)	1	15.15*	0.006ns	16.78ns	41.26**	50.67ns	0.003ns	15.52ns	5.93*	2.35ns	0.625ns
RC*PP	2	7.657**	0.09ns	6.97ns	21.97*	6.84ns	4.698ns	14.8ns	0.218ns	16.65*	44.06*
Residual	15†	1.686	5.66	10.39	4.51	29.36	16.62	7.88	1.347	3.78	10.39

† Residual DF at the Clay county site in 2006 and 2007 = 46, remaining sites = 15

* $P \leq 0.05$, ** $P < 0.01$; ns = not significant at $P = 0.05$

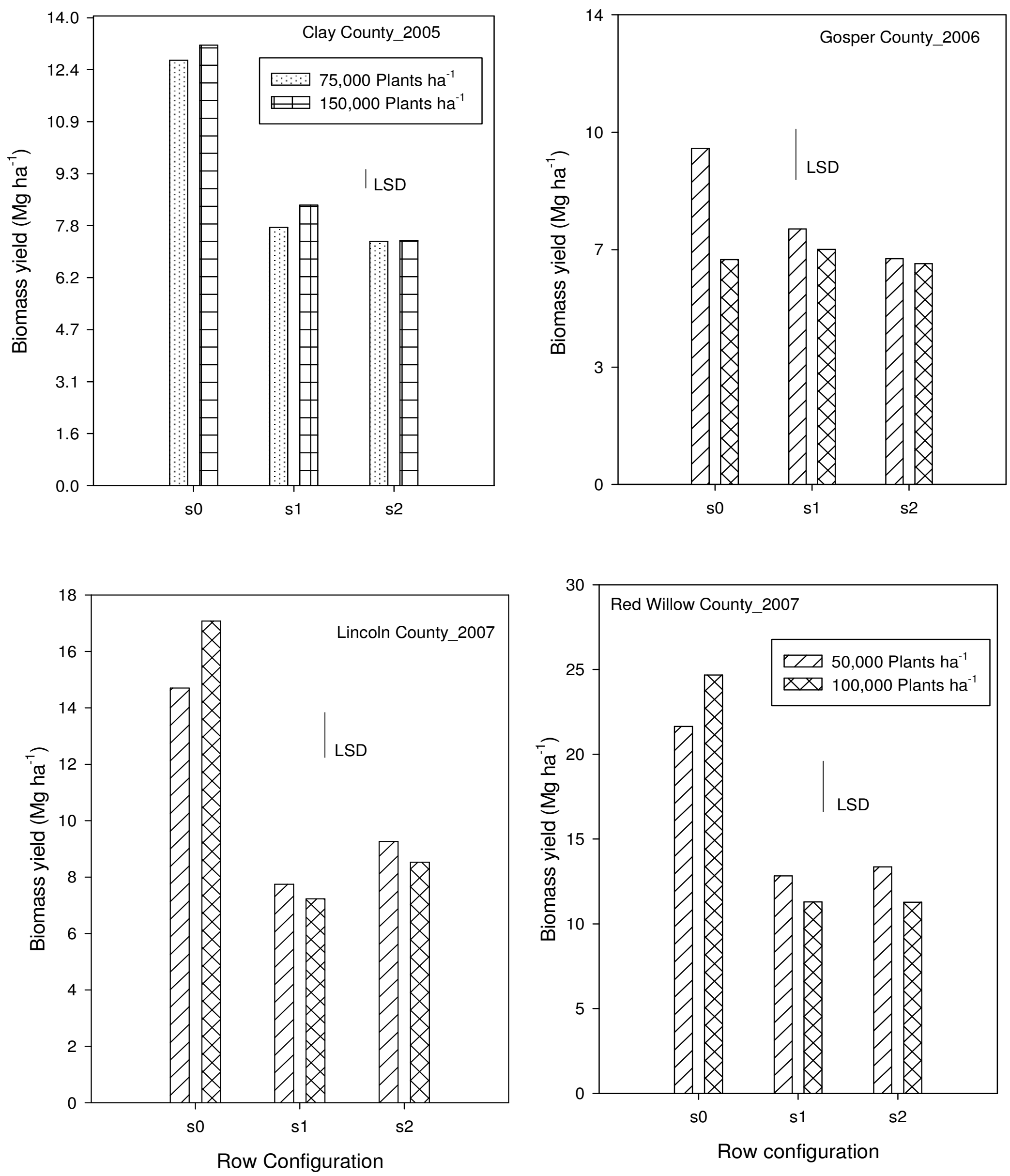

Figure 2.2. The effect of row configuration and plant population interaction on grain sorghum biomass yield at anthesis four site-years. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped. Y-bars = LSD at 0.05.

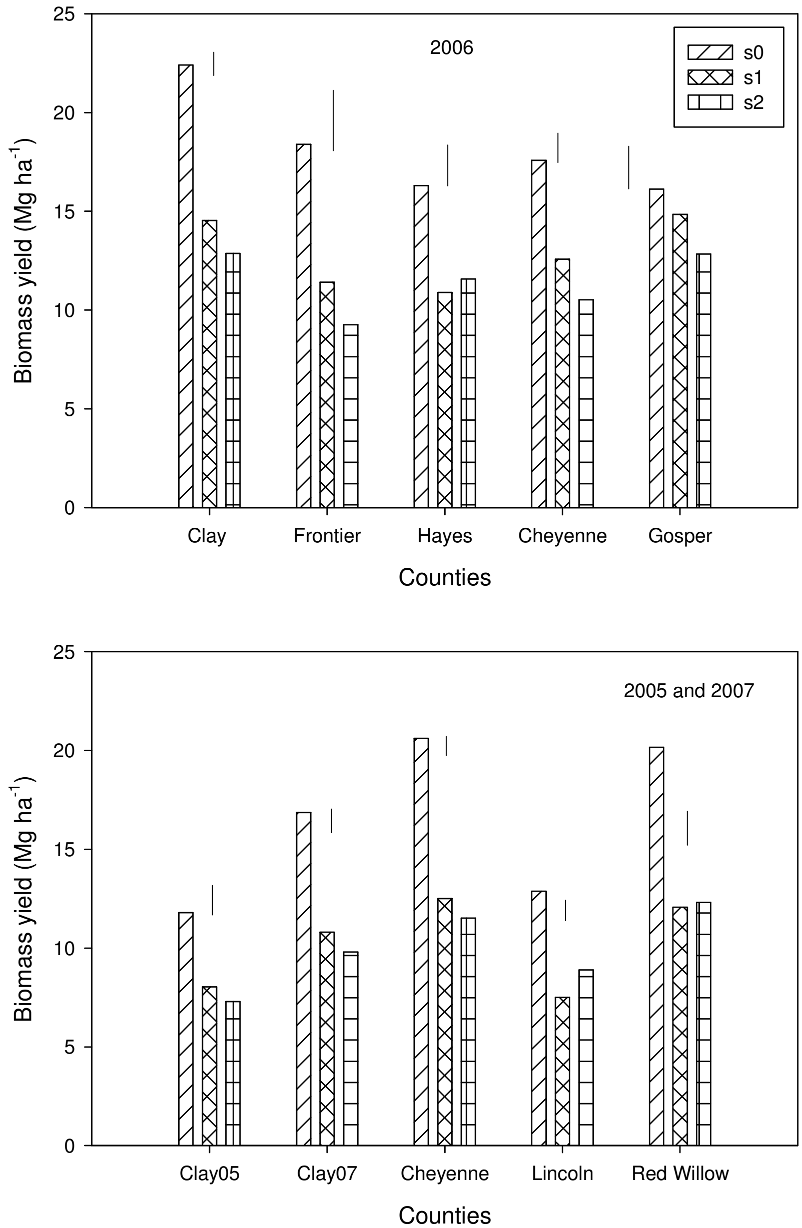

Figure 2.3. The effect of row configuration and plant population interaction on grain sorghum biomass yield at anthesis four site-years. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped. Y-bars = LSD at 0.05 at each site-year.

2.6.3 Grain yield

There were significant interactions between row configuration and plant population for grain yield in three out of the 10 sites-years; the Clay Co. site in 2006, Lincoln and Red Willow Co. sites in 2007 (Table 2.3). In all three years s0 produced higher grain yield than skip-row planting and s1 out-yielded s2 at the Clay Co. site (Figs. 2.4A and B). This agrees with other findings that yield potential can be reduced in high yielding environments when using wider rows due to the inability of the plant canopy to completely cover the ground area and efficiently utilize available resources (Myers and Foale, 1981; Holland and McNamara, 1982). The difference in grain yield between the low and high plant population (75,000 and 150,000 plants ha^{-1}) for the Clay Co. site were not consistent across years (Figs. 2.4 C and D). In 2005 and 2007, low population had higher grain yield than high plant population, but the reverse occurred in 2006.

At the Gosper, Frontier, Lincoln and Red Willow Co. sites, considered as medium rainfall sites, grain yield with skip-row planting was equal to or greater than s0 in 2006 (Fig. 2.4A) but in 2007 s0 grain yield was greater than with skip-row configurations at all sites except the Lincoln Co. site (Fig. 2.4B). Though the Gosper Co. site had total in-season precipitation higher than the 50-year average, 84% of the in-season rainfall events occurred after the flower stage. This affected panicle development and subsequently reduced s0 grain yield. Availability of soil water at the appropriate time generally has a larger effect on grain yield than total amount of water for many crops (Shaw, 1988). The Frontier and Cheyenne Co. sites had relative higher soil water with s1 and s2 at reproductive growth stages compared to the Hayes and Gosper Co sites (See Fig. 3.5). This led to higher grain yield with the skip-row configuration at Cheyenne and Frontier

compared with grain yield at Gosper and Hayes Co. sites. It has been reported that water stress at flower and grain fill stages of growth severely affects productivity of grain sorghum (Garrity et al., 1983; Hattendorf et al., 1988). In 2007, grain yield with s0 was higher than with s2 across all sites.

In 2007, while there were no differences in grain yield between s1 and s2 in the Lincoln and Cheyenne Co. sites, grain yield with s1 was greater than with s2 at the Clay and Red Willow Co. sites. At sites with moderate precipitation, grain yield was reduced by 18% with s2 and not affected with s1 compared with s0 in 2006 and 2007. At relatively high precipitation sites, grain yield was reduced by 20 to 35% with s1 and s2 compared to s0 across years.

At the Hayes and Cheyenne Co. sites in 2006, the driest environments, skip-row configurations produced significantly higher grain yield than the s0 (Fig. 2.4). The lower yield with s0 may be attributed primarily to less available soil water during the reproductive stages of crop growth. While there were no difference in grain yield between s1 and s2 at the Cheyenne Co. site, grain yield with s1 was higher than the s2 at the Hayes Co. site (Fig. 2.4A). In water deficit environments, grain yield increase of skip-row over conventional planting ranged between 5 and 123%. These results confirm findings of other studies which showed the grain yield advantage of skip-row planting of sorghum and corn over conventional planting under water deficit conditions (Holland and McNamara, 1982; Routley et al., 2003; Collins et al., 2006).

Routley et al. (2003) has shown that sorghum roots grow at rates of 15 to 40 mm day^{-1}, depending on the growth stage. If the rate of root growth (and therefore access to stored soil water) is assumed to average 25 mm day^{-1}, crops planted in narrow rows

exploit the available water by the time the crop reaches the critical flowering stage, in the absence of adequate in-season precipitation. Assuming this rate of root extension, the days of growth required to fully exploit soil water near the soil surface and at 120 cm depths are respectively 19 and 63 for s0, 38 and 71 for s1, and 57 and 82 for s2. With inadequate precipitation, conventional planting will deplete stored soil water earlier than skip-row planting. Under water stress conditions skip-row configuration will access stored soil water in the inter-row area at the critical growth stages to enhance yield potential. In 2006, soil water in the center of the skipped area at 750 mm depth with s2 was depleted at 45 DAP at the Hayes and Gosper Co. sites, while soil water drawdown continued until 75 DAP at the Cheyenne Co. site and 90 DAP at the Frontier Co. sites (Chapter 3. Fig. 3.5). At the Cheyenne Co. site in 2007, soil water with s0 was depleted at 70 DAP, s1 at 90 DAP while soil water drawdown continued with s2 until harvest. At the Clay Co. site in 2007, soil water drawdown with s0 started at 30 DAP, s1 started at 35 DAP and s2 at 50 DAP. However, in-season precipitation recharged soil water with all row configurations at 80 DAP (Chapter 3 Fig. 2.6).

There were significant differences in grain yield due to plant population in three out of ten site-years: at the Cheyenne Co. in 2006 and Clay Co. in 2006 and 2007. Sorghum can produce tillers to compensate for lower population, but the number of productive tillers is influenced by soil water availability. With good in-season precipitation and adequate stored soil water, productive tillers in the low population will produce grain yield comparable to high population (Thomas et al., 1980; Thomas et al., 1981; Myers and Foale, 1981; Berenguer and Faci, 2001).

Table 2.3. Summary of analysis of variance of grain yield (Mg ha^{-1}) of grain sorghum with three row configurations and two seeding rates at ten site-years.

		Clay 2005	Clay 2006	Clay 2007	Gosper 2006	Frontier 2006	Hayes 2006	Cheyenne 2006	Cheyenne 2007	Lincoln 2007	Red W. 2007
Source	DF	----------	----------	----------	----------	Mean square	----------	----------	----------	----------	----------
Row Config. (RC)	2	75.35**	63.11**	79.57**	1.168ns	3.686**	3.688**	0.154*	4.771**	0.856ns	1.516**
Plant Pop (PP)	1	1.388ns	1.22*	5.12*	0.58ns	1.237ns	0.362ns	1.861**	0.009ns	0.022ns	0.123ns
RC*PP	2	4.11ns	0.62*	0.40ns	0.20ns	0.239ns	0.44ns	0.024ns	0.142ns	4.47**	5.691**
Residual	15†	4.30	0.20	1.62	0.936	0.591	0.169	0.036	0.274	0.264	0.179

† Residual DF at the Clay county site in 2006 and 2007 = 46, remaining sites = 15

* P ≤ 0.05, ** P < 0.01; ns = not significant at P = 0.05.

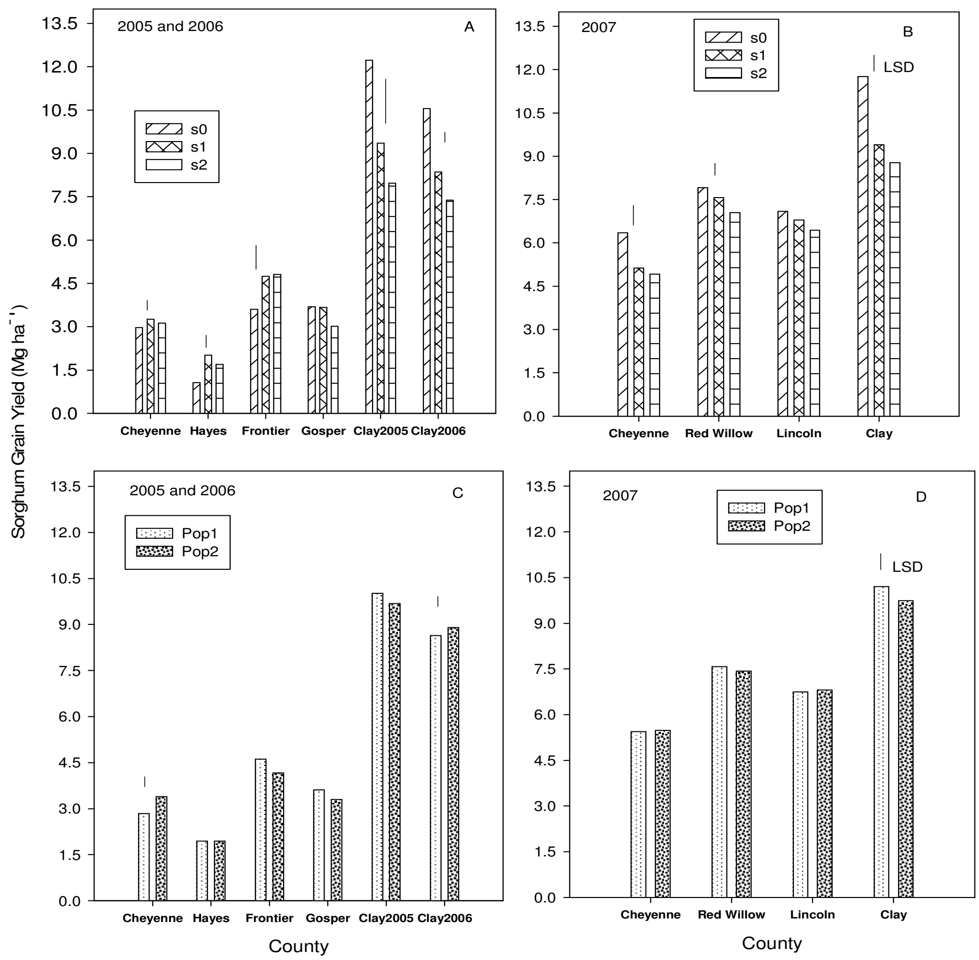

Figure 2.4. Effects of row configuration and low (50000 or 75000 seeds ha^{-1}) and high (100000 or 150000 seeds ha^{-1}) plant population on grain sorghum yield from 2005 to 2007 in Nebraska. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped. Y-bars = LSD at 0.05.

Considering the effects of planting configuration on yield across locations and rainfall regimes, there is a crossover at about 4.5 Mg ha^{-1}, with conventional planting outperforming skip-row planting when the average yield was above 4.5 Mg ha^{-1} (Fig. 2.5). The relationships between grain yield with s0 and with skip configurations (s1 and s2) across locations were established with coefficient of determination of 96 and 92% for s1 and s2, respectively. Similar trends have been observed elsewhere but at lower crossover values (Collins et. el., 2006; Routley et al., 2003).

There was a logarithmic relationship between available soil water at boot stage and grain yield at physiological maturity (Fig. 2.6). The threshold available soil water (minimum soil water required for grain yield) was lower with the skip-row configuration than with s0 configuration; 200 mm with s0 and 175 mm with skip-row configurations. At soil water below 320 mm, the skip-row configurations had a grain yield advantage over s0 configuration with a slope of 31.3 kg ha^{-1} mm^{-1} compared to 29.7 3 kg ha^{-1} mm^{-1} with s0. When soil water at boot stage was above 420 mm, s0 configuration had significantly higher grain yield mm^{-1} of available soil water than the skip row configurations.

The relationship between total in-season available water (soil water at planting plus 50-year average in-season total precipitation) was logarithmic with significant coefficients of determination of 88% with s0 and 81% with skip-row configurations (Fig. 2.7). If total in-season available water for a site was less than 650 mm (+/- 13.5 mm standard error), skip-row configuration had higher grain yield than s0 planting. There will be no yield advantage to a producer using skip-row configuration if the total in-season available water is more than 650 mm. However, actual distribution of in-season

precipitation as well as vapor pressure deficit, solar radiation, and wind speed may influence grain yield (Smika, 1983) and planting configuration.

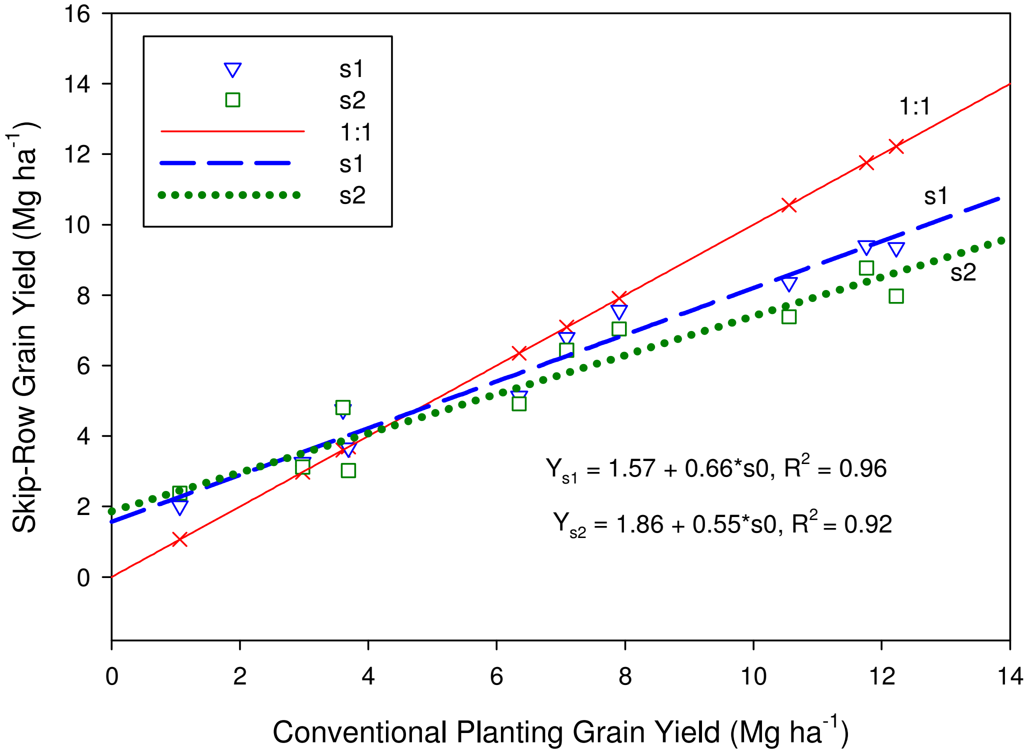

Figure 2.5. Relationship between grain yield with conventional and skip-row planting averaged over plant population in a 10 site-year study in Nebraska. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped.

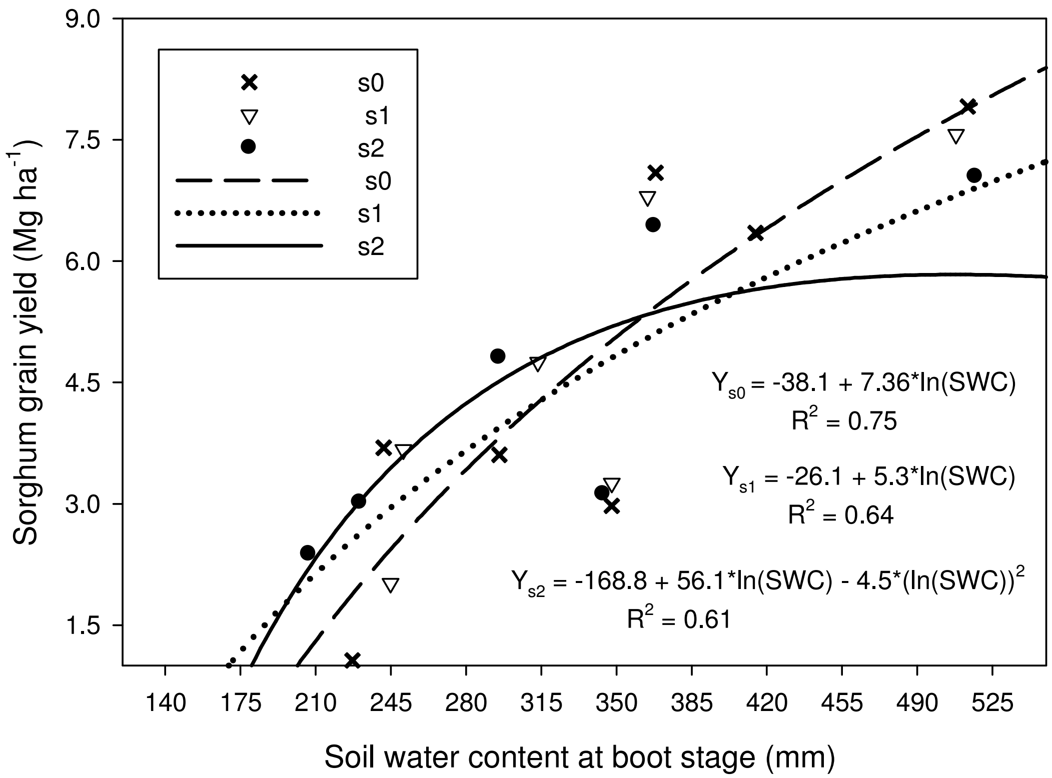

Figure 2.6. Relationship between soil water content at boot stage and grain yield across 10 site-years in Nebraska for three row configurations. Y= grain yield, s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped. SWC = Soil water content.

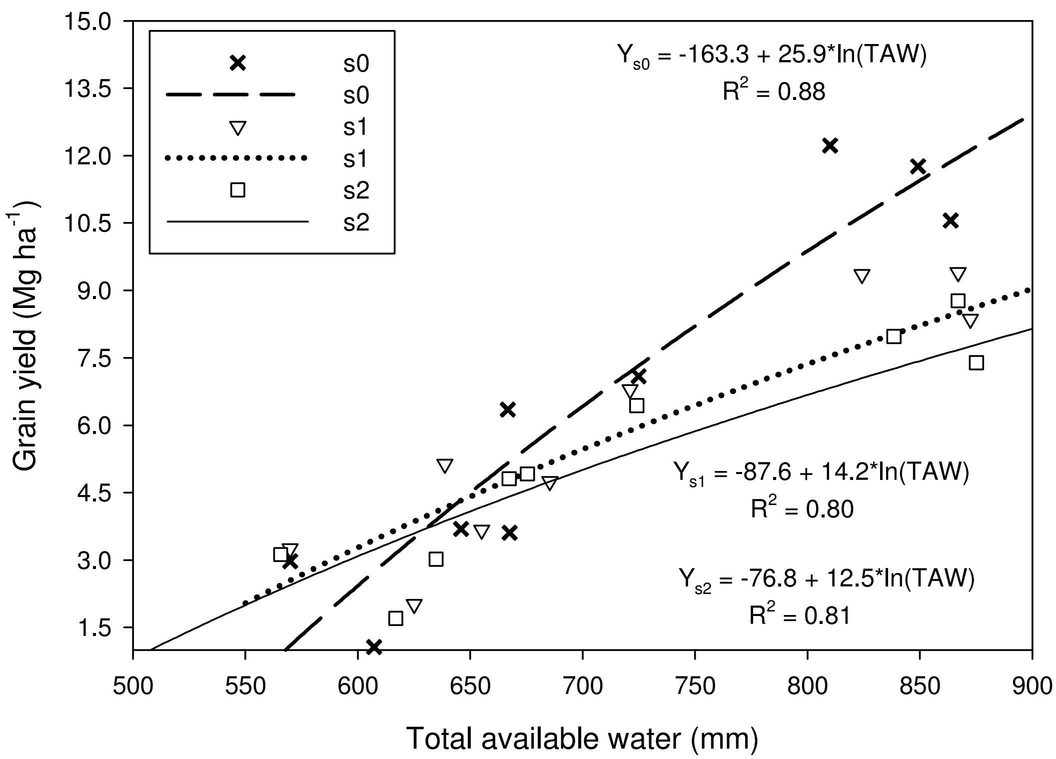

Figure 2.7. Relationship between total in-season available water (initial soil water plus long term in-season average precipitation) and grain yield across 10 site-years in Nebraska as affected by row configuration. Y = grain yield. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped. TAW = total available water.

2.6.4 Yield Stability

The method of Eberhart and Russell (1966) for estimating yield stability was adopted to estimate the stability of row configurations across sites. Grain yield was regressed against the environmental index (site mean) and the standard errors (SE) and slope of the regression equations were estimated and compared. In this study, stability is defined as row configuration that performed the same over the range of environments, indicating that row configuration did better under adverse conditions and not as well under favorable conditions.

There was a positive linear relationship between yield with each row configuration and the site mean (Fig. 2.8) with all treatment means improving with more favorable growing environment. The slope of the regression line was steepest for s0 indicating it is the most responsive to growing conditions compared with s1 and s2. Grain yield with s0 was least in the lower yield environments and highest in the high yield environments. A stable practice should have a low slope and deviations that were as small as possible from the regression (Eberhart and Russell, 1966; Lin et al., 1986; Becker and Leon, 1988; Braun et al., 1992). Grain yield was least stable with s0 as it had the highest SE and highest slope compared with s1 and s2. Improved environmental conditions will thus be more beneficial with s0, however, adverse environmental conditions will hurt s0 the most. The treatment with the smallest regression coefficient is the least responsive across site-years, as b = 0 for non-responsive treatment (Finlay and Wilkinson, 1963). Skip-row configurations had a slope of 0.9 with s1 and 0.75 with s2 compared to 1.33 with s0.

Plant one skip one configuration (s1) had the lowest SE across sites and a slope of less than one thus considered as more stable than s0 (Fig. 2.8). This may be attributed to the fact that with s0 water stress was severe and reduced grain yield significantly in low yield potential sites. The s1 and s2 had large inter-row areas for roots to exploit for water, thus improving grain yield. In high yield potential environments, s2 was not able to adequately use other resources such as solar radiation due to less canopy cover in the large inter-row area. With the lowest slope of 0.75, s2 is the least risky row configuration across sites, but has higher SE about the site mean compared to s1. Among the four general mechanisms for yield stability in sorghum proposed by Heinrich et al. (1983), yield component compensation was likely responsible for the high stability observed with the skip-row configurations.

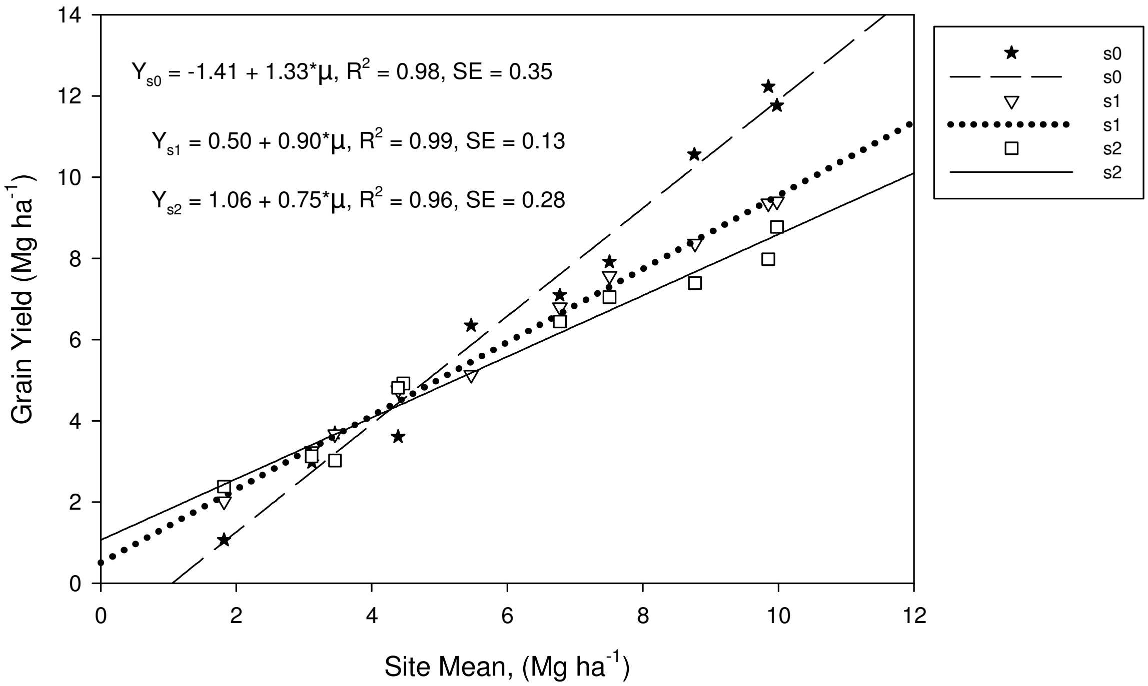

Figure 2.8. Yield response of three row configurations to yield potential across 10 site-years in Nebraska. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped.

2.6.5 Stover yield and harvest index at physiological maturity

Interactions between row configuration and population on stover yield at physiological maturity were observed at the Gosper Co. site in 2006 and the Lincoln Co. site in 2007 (Table 4). At the Gosper Co. site stover yield with s0 at both populations were higher than stover yield obtained with skip-row configurations at the same population (Fig. 2.9A). At the Lincoln Co. site high population with s1 out-yielded low population, however differences between the two plant populations with s0 and s2 were not present (Fig. 2.9B). In eight out of the ten site-years, s0 had higher stover yield than skip-row planting but differences between s1 and s2 were observed only at the Gosper, Frontier and Clay county sites in 2006 (Figs. 2.9C and D).

Row configuration x plant population interaction influenced harvest index (HI) at only one out of the ten sites-years (Table 2.5). However, skip-row configurations had higher HI than s0 at the Clay Co. site in 2005 and 2006, Gosper, Frontier and Hayes Co. sites in 2006 (Fig. 2.10). In general skip-row planting had significantly higher HI than the s0 configuration in drier years (2005 and 2006), suggesting more efficient partitioning of synthesized carbohydrate to the grain under water deficit conditions. Thus lower harvest index in s0 may be attributed to more non-productive tillers compared to skip-row configurations with higher within row plant population. Late tillers will compete with grain fill for photo-assimilate when soil water is inadequate to ensure complete tiller growth and development, and grain yield (Lafarge and Hammer, 2002).

Table 2.4. Summary of analysis of variance of stover yield (kg ha^{-1}) of grain sorghum with three row configurations and two plant population rates at ten site-years across Nebraska.

		Clay 2005	Clay 2006	Clay 2007	Gosper 2006	Frontier 2006	Hayes 2006	Cheyenne 2006	Cheyenne 2007	Lincoln 2007	Red W. 2007
Source	DF	----------------				Mean square					----------------
Row Config. (RC)	2	473.1**	322.9**	901.9**	58.72**	86.23**	117.2**	1.878ns	59.9**	8.44ns	794.7**
Plant Pop. (PP)	1	12.33ns	10.62ns	255.2**	6.84ns	0.51ns	2.97ns	15.46*	5.93*	0.03ns	1.20ns
RC*SR	2	0.04ns	3.57ns	3.65ns	17.30*	13.14ns	5.88ns	0.566ns	0.21ns	22.2*	6.08ns
Residual	15†	7.29	5.40	9.11	3.30	8.29	3.72	2.30	1.35	5.20	3.79

† Residual DF at the Clay county site in 2006 and 2007 = 46, remaining sites = 15

* $P \leq 0.05$, ** $P < 0.01$; ns = not significant at $P = 0.05$.

Table 2.5. Summary of analysis of variance of harvest index of grain sorghum with three row configurations and two plant population at ten site-years across Nebraska.

		Clay 2005	Clay 2006	Clay 2007	Gosper 2006	Frontier 2006	Hayes 2006	Cheyenne 2006	Cheyenne 2007	Lincoln 2007	Red W. 2007
Source	DF	Mean square									
Row Config. (RC)	2	0.052*	0.003**	0.037ns	0.026*	0.027**	0.053**	0.006ns	0.006ns	0.001ns	0.0003ns
Plant Pop. (PP)	1	0.001ns	0.0004ns	0.046ns	0.0004ns	0.024*	0.001ns	0.06**	0.001ns	0.0001ns	0.0001ns
RC*PP	2	0.0002ns	0.0006ns	0.037ns	0.003ns	0.003ns	0.014ns	0.01*	0.002ns	0.0025ns	0.001ns
Residual	15†	0.004	0.0004	0.023	0.005	0.004	0.005	0.002	0.018	0.0021	0.002

† Residual DF at the Clay county site in 2006 and 2007 = 46, remaining sites = 15

* $P \leq 0.05$, ** $P < 0.01$; ns = not significant at $P = 0.05$.

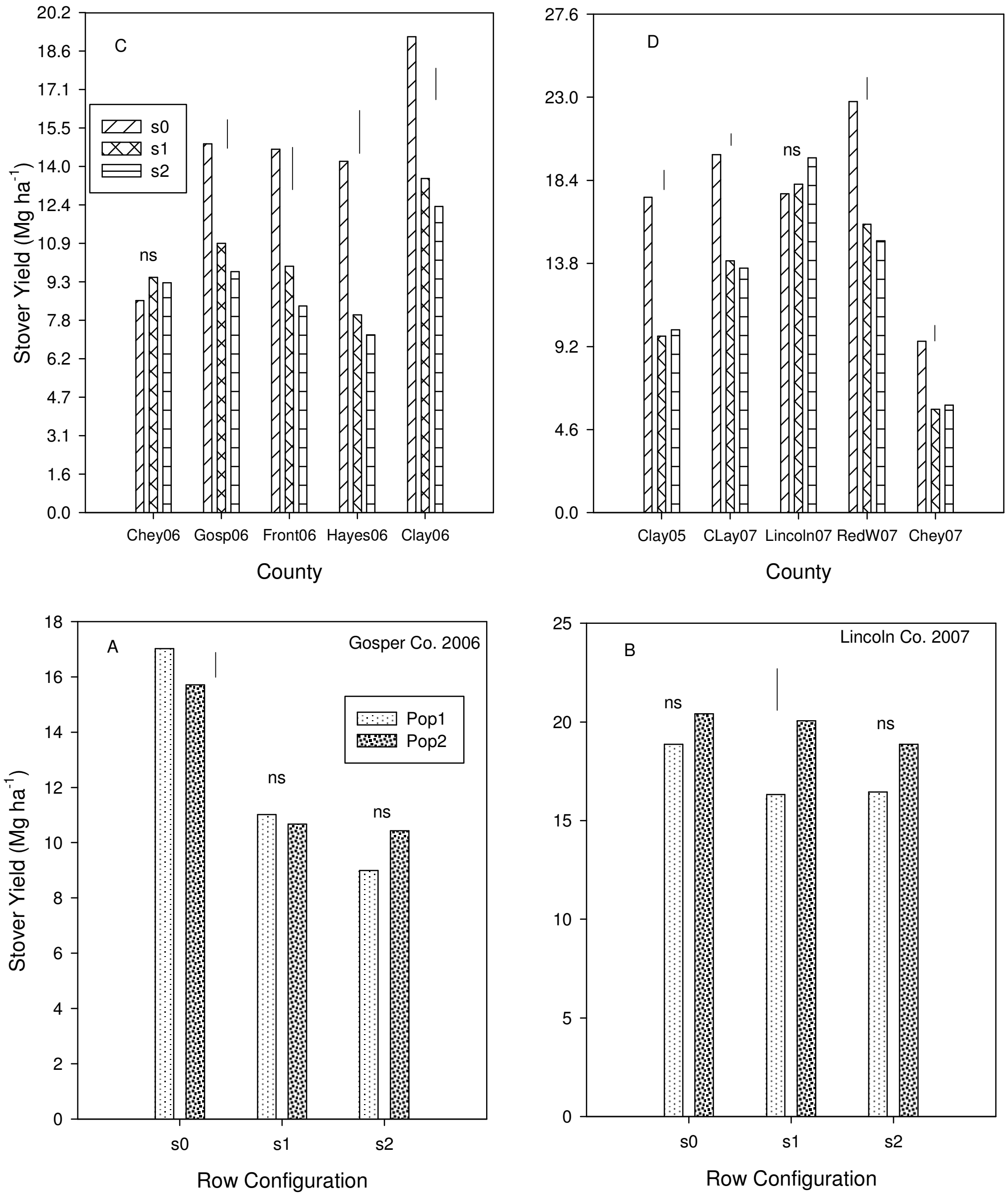

Figure 2.9. Effects of row configuration and low (50000 or 75000 seeds ha^{-1}) and high (100000 or 150000 seeds ha^{-1}) plant population on grain sorghum yield from 2005 to 2007 in Nebraska. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped. Y-bars = LSD at 0.05, ns = not significant.

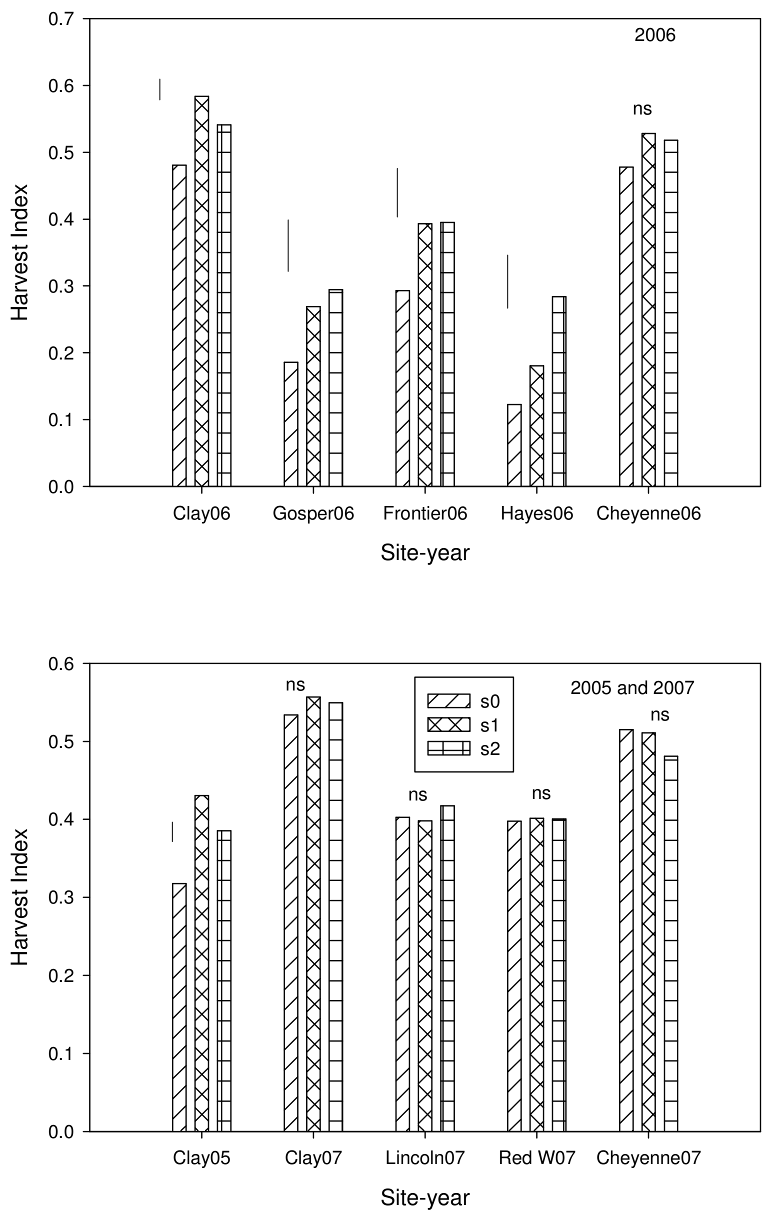

Figure 2.10. Effects of row configuration and low (50000 or 75000 seeds ha^{-1}) and high (100000 or 150000 seeds ha^{-1}) plant population on grain sorghum yield from 2005 to 2007 in Nebraska. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped. Y-bars = LSD at 0.05.

2.6.6 Yield components

At the Clay Co. site, there was no correlation between grain yield and grain yield per panicle, kernel weight, number of kernels per panicle and number of panicles m^{-2}. At the medium and the low rainfall sites grain yield was significantly influenced by grain yield per panicle, number of kernels per panicle and number of panicles m^{-2} (Table 2.6). Grain yield per panicle was influenced by kernel weight and number of panicle m^{-2} in the high rainfall site, and number kernels per panicle and kernel weight in the medium and low rainfall sites. These results are generally in agreement with those of Maman et al. (2004), although they did not find any association between number of kernels per panicle and kernel weight. Both number of kernels per panicle and kernel weight has association with other yield components across all sites and is a major contributing factor to grain yield (Saeed et al., 1986; Heinrich et al., 1985). Sorghum grain yield in combination with yield components differences reflect the presence and timing of stress conditions or differences in production practices (Maman et al., 2004).

Row configuration x plant population interaction affected number of panicles m^{-2} at five site-years, kernel weight at three site-years, grain yield per panicle at one site-year and number of kernels per panicle at one out of the 10 site-years (See Tables 2A-D). Skip-row configurations had higher or equal grain yield per panicle than s0 in all 10 site-years (Table 2.7). The influence of row configuration on grain yield per panicle was more pronounced in the medium and low rainfall sites-years than high rainfall site-years. Skip-row configurations had higher number of panicles m^{-2} than s0 in six out of the 10 site-years and higher grain yield per panicle in five site-years.

In high rainfall site-years, higher grain yield per panicle with skip-row configurations suggests a potential benefit of skip-row planting even in high yield potential site. Since row spacing will affect the interception of solar radiation, reducing the base row spacing of 76 cm in a high yield potential environment with skip-row planting may improve utilization of soil water and nutrients and thus increase grain yield. Limon-Ortega et al. (1998) reported that using narrow row spacing of 38 cm gave higher grain yield of sorghum than using 76 cm row spacing in eastern Nebraska. The study attributed the increased grain yield of narrow spacing to production of more panicles m^{-2}. In moderate to low rainfall environments, grain yield per panicle with skip-row configuration was higher than that of s0 configuration except at the Gosper Co. site where in-season precipitation was 120% of the 50-year average for the county.

One-hundred kernel weight ranged from 2.0 g at the Cheyenne Co. site, a low yield environment to 4.3 g at the Clay Co. site in 2007, a high yield environment (Table 2.7). In three of ten site-years, skip-row configuration had higher kernel weight than s0. At the remaining sites, row configuration did not affect kernel weight. Considering the fact that grain yield per panicle and harvest index were significantly influenced by row configuration, it stands to reason that higher grain yield observed in the skip-row treatments were influenced by the number of panicles m^{-2}. This results support the view that grain crops are more sensitive to water stress during the flowering and grain filling stage and that kernel weight, grain weight per panicle and kernel number are reduced by water stress (Doorenbos and Kassam, 1979; Thomas et al. 1981; Wade and Douglas, 1990; Berenguer and Faci, 2001). The number of panicles m^{-2} and number of kernels per panicle are determined early in plants life cycle and during the reproductive period.

According to Evans and Wardlaw (1976), and Eastin et al. (1999), water stress during the reproductive stage will affect number of kernels irreversibly and adequate soil water after this growth stage will have limited increase in kernel weight.

At the Clay Co site in all the three years, high plant population had higher number of panicles m^{-2} than low plant population. However, low plant population had higher number of kernels per panicle and higher grain yield per panicle (Table 2.8). At the Gosper and Frontier Co sites in 2006, high plant population had higher number of panicles m^{-2} and higher grain yield per panicle than the low population. At the Hayes and Cheyenne Co sites in 2006, low plant population had higher number of plants m^{-2} than high plant population. At low plant stand, grain sorghum produce higher number of tillers compared to recommended plant density (Gerik and Neely, 1987; Schatz et al., 1990; LaFarge and Hammer, 2002; Conley, 2005). Larson and Vanderlip (1994) suggested that grain sorghum ability to compensate for decreased plant density was related to plant space uniformity. The number of panicles m^{-2} are determined early in plants life cycle and are influenced by environmental factors such as temperature and water. The ability of the tiller to produce panicle and the number kernels per panicle are affected by water stress (Eastin et al., 1999). Water stress will affect number of panicle and number of kernels per panicle irreversibly and adequate soil water after reproductive stage will have limited increase in kernel weight.

Plant population did not influence kernel weight at any of the 10 site-years and influenced number of kernels per panicle at three out of the 10 site-years. Important yield compensation processes which may include productive tiller production, number of grains per panicle and panicle weight may have compensated for lower population. This

may explain why in general the higher population did not provide an advantage in sorghum grain yield. Under water stress conditions, the crop will manipulate its yield components, grain size, number of grains per panicle and ultimately its harvest index (Norwood, 1992; Thomas et al., 1981).

Table 2.6. Pearson correlation coefficient among yield and yield components of grain sorghum across rainfall environments at Nebraska.

	Grain yield	Grain yield panicle^{-1}	Kernel weight	Kernels panicle^{-1}
	----------Correlation coefficient----------			
High rainfall site[†]				
Grain yield				
Grain yield panicle^{-1}	-0.15			
Kernel weight	-0.16	0.96**		
Kernels panicle^{-1}	-0.33	0.34	0.52*	
Panicle m^{-2}	-0.47	0.87**	0.80**	0.29
Medium rainfall sites[‡]				
Grain yield				
Grain yield panicle^{-1}	0.81**			
Kernel weight	-0.30	-0.25		
Kernels panicle^{-1}	0.80**	0.99**	-0.36	
Panicle m^{-2}	0.22	0.24	0.51*	0.17
Low rainfall sites[#]				
Grain yield				
Grain yield panicle^{-1}	0.59*			
Kernel weight	0.21	-0.58*		
Kernels panicle^{-1}	0.30	0.93**	-0.84**	
Panicle m^{-2}	0.50*	0.08	0.59*	-0.22

[†] Clay County site, [‡]Gosper, Frontier, Lincoln and Red Willow Co. sites,

[#] Hayes and Cheyenne Co. sites. * Correlation is significant at $P \leq 0.05$,

** Correlation is significant at $P \leq 0.01$

Table 2.7. Effect of row configuration on sorghum grain yield per panicle and kernel weight in 10 site-years in transect across Nebraska. Values followed by a different letter within site-year were significantly different at P ≤ 0.05.

County	Year	Row Configuration	Grain yield panicle^{-1} -----g-------	100 kernel weight -----g------	Kernels panicle^{-1}	Panicle m^{-2}
Clay	2005	s0	71.74 a	4.252 a	1683 a	18.0c
		s1	77.46 a	4.358 a	1784 a	25 .0b
		s2	79.15 a	4.379 a	1805 a	35.0a
Clay	2006	s0	39.41 a	3.060 b	1829 a	10.0b
		s1	40.15 a	3.178 a	1749 a	15.0a
		s2	40.84 a	3.077 b	1852 a	13.0a
Clay	2007	s0	37.06 b	2.552 b	1459 a	11.0b
		s1	44.81 a	2.722 a	1653 a	15.0a
		s2	41.08 b	2.734 a	1458 a	16.0a
Gosper	2006	s0	28.42 ns	2.669 a	1017 a	9.0b
		s1	29.16 ns	2.801 a	1080 a	15.0a
		s2	29.93 ns	2.876 a	1052 a	14.0a
Frontier	2006	s0	21.11 b	2.947 a	737 b	16.0a
		s1	35.70 a	3.032 a	1178 a	18.0a
		s2	32.70 a	3.063 a	1061 a	16.0a
Hayes	2006	s0	18.32 b	2.698 a	705 b	9.0a
		s1	22.64 b	2.830 a	800 b	9.0a
		s2	32.57 a	2.720 a	1185 a	9.0a
Cheyenne	2006	s0	49.84 b	1.948 a	2588 a	8.0a
		s1	60.76 a	2.088 a	2916 a	7.0a
		s2	55.82 ab	2.043 a	2741 a	8.0a
Cheyenne	2007	s0	45.51 a	2.779 a	1640 a	9.0b
		s1	51.35 a	2.799 a	1834 a	15.0a
		s2	49.13 a	2.786 a	1764 a	14.0a
Lincoln	2007	s0	32.06 b	2.575 b	1257 b	12 a
		s1	60.69 a	2.605 ab	2340 a	13 a
		s2	63.03 a	2.772 a	2334 a	13 a
Red Willow	2007	s0	54.20 a	2.923 a	1864 a	15.0b
		s1	60.61 a	2.821 a	2149 a	17.0ab
		s2	56.21 a	2.780 a	2029 a	22.0a

Table 2.8. Effect of plant population on sorghum grain yield per panicle and kernel weight in 10 site-years in transect across Nebraska. Values followed by a different letter within site-year were significantly different at P ≤ 0.05.

County	Year	Plant pop x 1000	Grain yield $panicle^{-1}$ ------g-------	100 kernel weight ------g-----	Kernels $panicle^{-1}$	Panicle m^{-2}
Clay	2005	75	53.2a	4.35a	1903a	15.0b
		150	49.7a	4.31a	1611a	19.0a
Clay	2006	75	44.4a	3.11a	1998a	12.0b
		150	35.9b	3.10a	1622b	14.0a
Clay	2007	75	46.7a	2.71a	1723a	12.0b
		150	35.2b	2.62a	1324b	15.0a
Gosper	2006	50	18.4a	2.78a	1029a	12.0a
		100	19.1a	2.78a	1071a	14.0b
Frontier	2006	50	23.8b	3.06a	1061b	15.0b
		100	25.1a	3.00a	1187a	19.0a
Hayes	2006	50	10.9b	2.83a	697b	10.0a
		100	16.0a	2.68a	1114a	8.0b
Cheyenne	2006	50	53.8a	1.99a	2716a	9.0a
		100	57.1a	2.07a	2780a	7.0b
Cheyenne	2007	50	47.8a	2.80a	1704a	12.0b
		100	49.6a	2.77a	1789a	15.0a
Lincoln	2007	50	49.3a	2.62a	1902a	13.0a
		100	54.5a	2.67a	2052a	12.0a
Red Willow	2007	50	60.5a	2.84a	2132a	17.0a
		100	53.5a	2.84a	1987a	17.0a

2.7 Conclusions

This study was conducted across southern Nebraska to evaluate the effect of row configuration and plant population on stored soil water availability and grain sorghum yield. At higher rainfall sites, skip-row configuration resulted in yield loss between 20 and 30% compared to s0. At the lowest rainfall sites, s1 and s2 out-yielded s0 by 5 to more than 100% in 2006. However, in the third year of the study, with higher average precipitation fairly well distributed throughout the growing season at all the study sites, skip-row planting, especially s2, resulted in reduced yield at all sites. Skip-row configuration improved harvest index and grain yield per panicle at medium and low rainfall sites. Skip-row planting is predicted to out-yield s0 when mean yields are less than 4.5 Mg ha^{-1}. If total available water for a site is less than 650 mm, skip-row configuration is predicted to yield more than s0 planting. Conventional planting will produce higher yield when total in-season available water is more than 650 mm. Skip-row planting was less responsive to environmental changes and thus less risky in production environments with lower and unpredictable in-season precipitation.

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CHAPTER THREE

EFFECT OF SKIP-ROW CONFIGURATION AND PLANT POPULATION ON SOIL WATER AVAILABILITY, CROP WATER USE AND WATER USE EFFICIENCY IN GRAIN SORGHUM IN NEBRASKA.

3.1 Abstract

Grain sorghum (*Sorghum bicolor* (L.) Moench) is commonly produced in semi-arid areas and yield is often constrained by soil water deficits. When soil water is adequate throughout the growing season equal spacing of sorghum rows typically results in the highest grain yield. Skip-row planting is a means of conserving soil water for later growth stages and may result in higher yields when severe water deficits occur during the reproductive stage. Field research was conducted at 10 site-years from 2005 to 2007 in a transect across Nebraska where annual mean precipitation ranges from 300 to 900 mm yr^{-1} to determine the effect of row configuration and population on stored soil water, crop water use and water use efficiency in grain sorghum production. Three row configurations including all rows planted (s0), alternate rows planted (s1), and two rows planted alternated with two rows skipped (s2) were evaluated in a complete factorial with two plant populations. Soil water content was measured to 1200 mm depth biweekly with a neutron moisture meter. At anthesis, crop water use efficiency (WUE) was higher with s0 compared with skip-row configuration. At physiological maturity, WUE was highest with skip-row configuration at site-years with mean in-season precipitation < 2mm day^{-1} and lower at sites where the mean in-season daily precipitation was > 2.5 mm. Residual

soil water in the skip-row configurations was 10 to 35 mm higher compared with s0 across site-years.

3.2 Introduction

In the semiarid regions plant available water is often the most critical factor limiting crop growth and yield potential in dryland agriculture. Sorghum has an extensive rooting system that can extract soil water to a soil depth of 3.0 m, is drought tolerant and often adapted to semi-arid dryland farming (Jones and Johnson, 1983; Shackel and Hall, 1984). Severe water deficits during the early reproductive and grain filling stages of growth is a common major cause of low grain yield and total crop failure. According to Craufurd et al. (1993), water stress at boot and flower stages can result in grain yield reduction of up to 85%.

Sorghum is planted in the semi-arid Central Great Plains in mid to late spring when soil water is usually adequate for good emergence and vegetative growth. When in-season precipitation is inadequate, however, soil water is depleted and stress occurs during the critical stages of flowering and grain fill, resulting in reduced grain yield and sometimes total crop failure. Water stress at anthesis in determinate crops reduces yield disproportionately below that supported by the total amount of water available for growth (Ockerby et al., 2001). Therefore a crop production strategy which can improve soil water availability at reproductive growth stages could improve water use efficiency (WUE) and increase grain yield. Generally grain crops are more sensitive to water deficit during flowering and early seed formation stage than during vegetative and ripening stage (Doorenbos and Kassam, 1979; Garrity et al., 1983). Maman et al. (2003) reported that

water supplied at grain fill stage had more impact on total grain yield than at boot stage or if supplied in multiple irrigations.

Skip-row planting can conserve soil water for later use by the crop (Blum and Naveh, 1976; 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 than conventional planting where mean yield potential of grain sorghum was less than 3 Mg ha^{-1}. Planting in 1.5 m wide rows and 1 m row with a skip-row configuration prevented total crop failure and out-performed conventional planting with base 1 m row spacing in dry years (Routley et al., 2003; Whish et al., 2005).

Grain sorghum can tiller when there is adequate early season soil water and more tillers are produced if the plant population is low (De Witt et al., 1977; Thomas et al., 1980). This defeats the objective of conserving soil water with low seeding rates. However, other studies indicated that wide row spacing with high seeding rate reduces tillering, dry matter yield and early water use with the benefit of saving soil water in the skipped area for use by the plant during the flowering and grain fill stages (Blum and Naveh, 1976; Thomas et al., 1980). Under soil water deficit conditions, water and nutrient use is inefficient when leaf development on tillers ceases and tillers do not produce grain (Lafarge and Hammer, 2002). Sinclair et al. (1984) defined WUE as a ratio of biomass accumulation expressed as total crop biomass or grain yield to water consumed expressed as transpiration, evapotranspiration or total water input to the system.

3.3 Hypothesis and objectives

The hypotheses of this study was that the interaction of skip-row configuration and plant population would retain stored soil water in the skipped area for efficient utilization during the reproductive growth stage during relative dry years, leading to improved crop water use and water use efficiency. The general objective of the study was to evaluate the relationship between row configuration and plant population in soil water extraction pattern and storage to achieve the highest ratio of grain yield to water use. The specific objectives were to compare the effect of row configuration and population on:

i. Compare soil water availability and residual stored water under skip-row configuration grain sorghum production to conventional planting configuration.
ii. Pattern of soil water extraction during the season.
iii. Crop water use and water use efficiency.

3.4 Materials and Methods

From 2005 to 2007 field studies were conducted at seven locations and 10 site-years across Nebraska to evaluate the effect of row configuration and plant population of grain sorghum on crop water use and water use efficiency (Table 3.1). See chapter 2 for experimental design, treatments, agronomic practices at each site-year and statistical analysis.

To measure volumetric soil water content, neutron probe access tubes were installed in the center of the skipped area of s1 and s2 configurations and in the center between two rows of s0 configuration at each site. Volumetric soil water content was

measured weekly at the Clay and Cheyenne Co. sites but every other week at the Gosper, Frontier, Hayes, Lincoln and Red Willow Co. sites. Volumetric soil water content measurement began three weeks after planting until physiological maturity, using a neutron probe (Troxler 4301, Troxler Electronic Labs. Research Triangle Park, NC, USA) at depths of 300, 600, 900, 1200 mm at all sites. In-season precipitation, and reference evapotranspiration data were collected from the nearest Automated Weather Data Network site.

In 2006 and 2007, Watermark sensors (Irrometer Co. Riverside, CA, USA) were installed at 750 mm depth in the center of the skip area of s2 configuration at all sites to monitor when roots of sorghum started utilizing stored soil water from the inter-row area. Soil matric potential was logged every 30 minutes by a data logger connected to each sensor. The soil matric potential (measured in kPa) was converted to volumetric water content (m^3 m^{-3}) using the Saxton Equation solution for soil water characteristics (Saxton and Rawls, 2006). Permanent wilting point and field capacity values at various study sites were estimated using the Saxton Equation solution for soil water characteristics (Saxton et al., 1986).

Crop water use (CWU), considered to be evapotranspiration was estimated at anthesis and physiological maturity as:

CWU at anthesis (mm) = SWC (soil water content at the first post-sowing measurement) + in-season precipitation up to anthesis - SWC at anthesis - deep percolation - runoff.

CWU at physiological maturity (mm) = SWC (soil water content at the first post-sowing measurement) + in-season rainfall up to physiological maturity - SWC at physiological maturity - deep percolation – runoff

(Angus and Herwaarden, 2001; Routley et al., 2003, Maman et al., 2003).

Observation at study sites suggested that deep percolation and runoff were negligible, so these components were not used in CWU calculations.

Water use efficiency was calculated as:

WUE at anthesis (kg ha^{-1} mm^{-1}) = dry matter yield at anthesis / CWU at anthesis

WUE at physiological maturity = grain yield / CWU at physiological maturity

(Sinclair et al., 1984).

Table 3.1. Soil series, taxonomic classes, agronomic data and rainfall at each study site.

Site, soil and agronomic data	County Clay	Gosper	Frontier	Hayes	Cheyenne	Red Willow	Lincoln
Location	lat.40°34'N; long.98°08W; 543.3 m elev	lat.40°28'N; long.99°53W; 732 m elev	lat.40°40'N; long.100°29W; 829 m elev	lat.40°30'N; long.101°01W; 922.0 m elev	Lat. 41°12'N; 103°01'W; 1317 m elev.	Lat. 40°23'N 100°58'W; 792 m elev.	Lat. 41°05'N; 100°75'W; 922 m elev.
Soil series	Crete silt loam	Holdrege silt loam	Hall silt loam	Kuma silt loam	Duroc loam	Holdrege & Keith silt loam	Holdrege silt loam
Taxonomic class	fine, smectitic, mesic Pachic Arguistolls	Fine-silty, mixed, superactive, mesic Typic Argiustolls	Fine-silty, mixed, superactive, mesic Pachic Arguistolls	Fine-silty, mixed, superactive, mesic Pachic Arguistolls	Fine-silty, mixed, superactive, mesic Pachic Haplustolls	Fine-silty, mixed, superactive, mesic Typic/Aridic Argiustolls	Fine-silty, mixed, superactive, mesic Typic Argiustolls
Previous crop	Corn	Corn	Corn	Corn	Wheat, Corn	Corn	Corn
Variety	Dekalb 42-20	Dekalb 29-28	Dekalb 29-28	Dekalb 29-28	Dekalb 29-28	Dekalb 29-28	Dekalb 29-28
Plant Pop	75,000/ha 150,000/ha	50,000/ha 100,000/ha	50,000/ha 100,000/ha	50,000/ha 100,000/ha	50,000/ha 100,000/ha	50,000/ha 100,000/ha	50,000/ha 100,000/ha
Plant date	May 24, 2005	May 16, 2006	May 23, 2006	May 24, 2006	June 1, 2006	May 24, 2007	Jun. 1, 2007
Harvest date	Oct. 14, 2005	Oct. 31, 2006	Oct. 31, 2006	Nov. 1, 2006	Oct. 17, 2006	Oct. 2, 2007	Oct. 2, 2007
Plant date	June 7, 2006				June, 2007		
Harvest date	Oct. 25, 2006				Oct. 3, 2007		
Plant date	June 6, 2007						
Harvest date	Oct. 10, 2007						

3.6 Results and Discussion

3.6.1 In-season precipitation and reference (alfalfa) evapotranspiration across sites

Total in-season precipitation at Clay Co. site in 2005 (Fig. 3.1A) amounted to 71% of the 50-year average in-season precipitation of 495 mm. Total weekly precipitation ranged from 0 to 43 mm with the highest in-season rainfall event occurring between 60 and 65 DAP. Weekly total reference evapotranspiration (ET_R) was higher than weekly precipitation in most of the growing season, ranging between 23 and 66 mm. The lowest in-season precipitation period during the season occurred between 20 and 60 DAP where the weekly precipitation accounted for less than 19% of the weekly ET_R.

The in-season precipitation at Clay Co. site in 2006 (Fig. 3.1B) ranged from 0 to 56 mm per week while weekly total ET_R ranged from 24 to 62 mm. Weekly total precipitation exceeded ET_R or the difference between the two was lowest during flowering and grain fill stages of growth. Weekly total precipitation at the Clay Co. site in 2007 ranged from 1.27 to 60 mm and provided 120% of the 50-year average total in-season precipitation (Fig. 3.1C). From boot to grain fill stage, weekly total precipitation either exceeded or accounted for more than 50% of the weekly total ET making it the season with greatest rainfall in the 3-year study at the site. The total in-season precipitation at Frontier Co. site, 390 mm, Hayes Co. site, 376 mm, and Gosper Co. site was 496 mm (Figs. 3.1D, E, F). These values represented 87, 100 and 119% of the 50-year average of total in-season precipitation for these counties. Though Frontier Co. site had lower in-season precipitation compared with Gosper and Hayes sites, rainfall events were better distributed during the growing season. At Hayes Co. site, there was a dry spell during the reproductive (60 to 80 DAP) growth stage of the crop. More than 80% of

the in-season precipitation at Gosper Co. site occurred during the post-vegetative growth stage (60 DAP). At the Cheyenne Co. site in 2006 (Fig. 3.1G), the weekly total precipitation ranged from 0 to 55 mm with total in-season of 261 mm, constituting 82% of the 50-year average total in-season precipitation. Weekly total ET_R ranged from 30 to 77 mm during the growing season. A dry spell occurred from 50 and 90 DAP where in-season precipitation accounted for less than 20% of the weekly total ET_R demand

The Lincoln Co. site (Fig. 3.1H) had 109% and the Red Willow Co. site (Fig. 3.1I) had 121% of the 50-year average total in-season precipitation of 377 mm and 388 mm, respectively. At the Lincoln Co. site total weekly precipitation ranged from 0 to 46 mm and total weekly ET_R from 33 to 56 mm. At the Red Willow Co. site total weekly precipitation was 0 to 91 mm and ET_R was 30 to 62 mm. While 24% of the total in-season ET_R demand was accounted for by precipitation at the Lincoln Co. site, 38% of ET_R demand was accounted for by precipitation at the Red Willow Co. site. The Cheyenne Co. site in 2007 (Fig. 3.1J) had 77% of the 50-year average in-season precipitation compared with 82% in 2006 (Fig. 3.1F). However, rainfall events in the 2007 growing season were more evenly distributed with no prolonged dry spell as observed in 2006. The weekly total ET_R ranged between 38 and 69 mm and the weekly in-season precipitation in the reproductive growth stages accounted for 31% of the weekly ET while in 2006 only 7% ET_R demand was supplied by precipitation during the same growth stage.

Excesses of ET_R over precipitation are accounted for by loss of stored soil water. The lower the in-season precipitation, the higher the amount of stored soil water extracted and the lower the residual soil water. When there is not enough stored soil water to meet

ET demand (higher ET_R/precipitation ratio), the crop will be water-stressed, and photosynthetic processes and carbohydrate synthesis will decrease, and grain yield will be adversely affected. During the flowering and grain fill stages (II and III), ET_R/ precipitation ratio, an indicator of water stress (Maman et al., 2003) was more pronounced in 2005 compared with 2006 and 2007 at the Clay Co. site (Table 3.2). The Cheyenne Co. site had higher water stress in 2006 than 2007, and the Lincoln Co. site had two times higher water stress than the Red Willow Co site in 2007 (Table 3.2). Generally, maximum air temperature across sites peaked during the reproductive growth stages (II and III) but declined as the crop matured (Table 3.2).

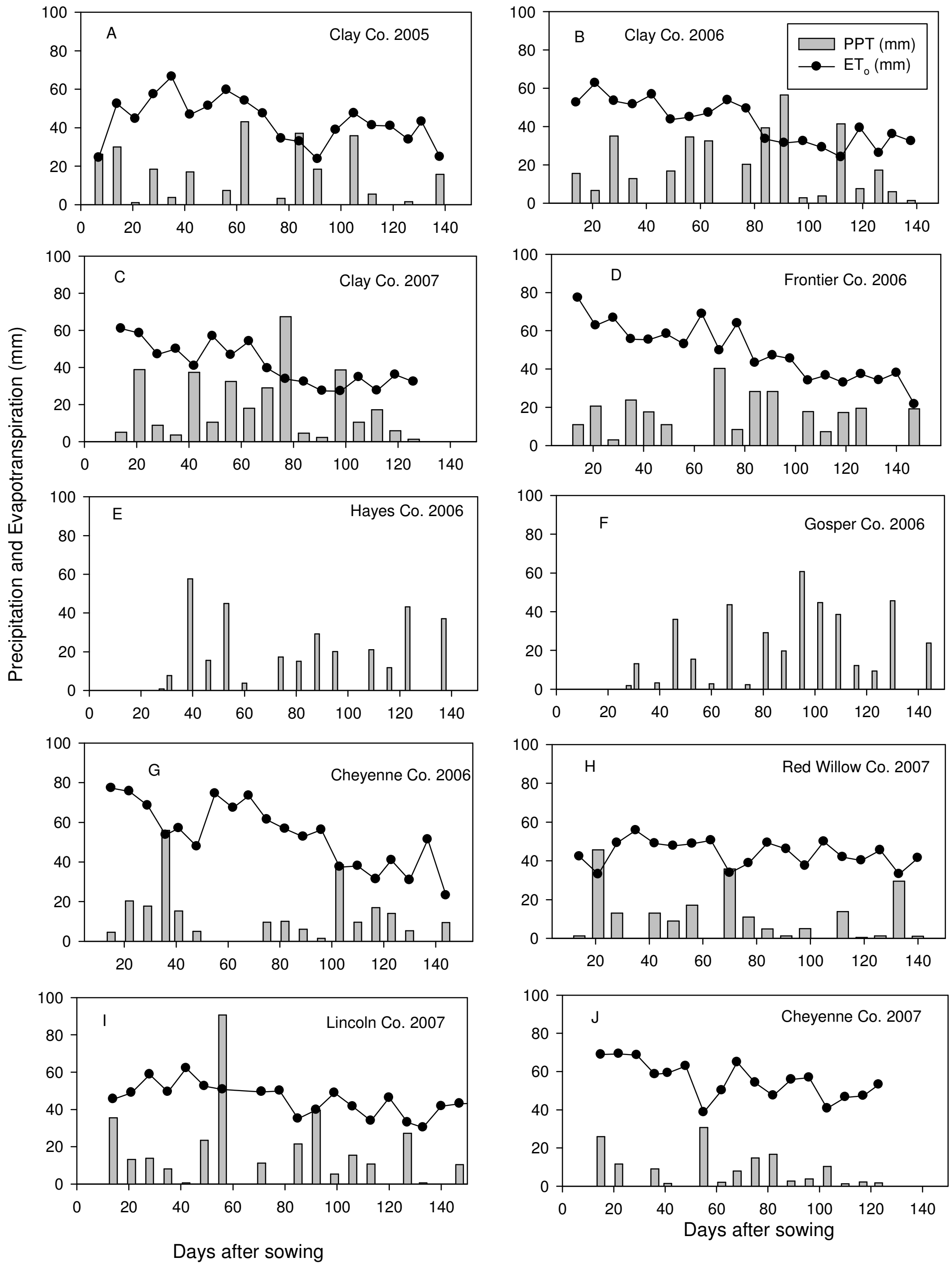


Figure 3.1. In-season precipitation (precipitation, bar) and reference (alfalfa) evapotranspiration (ET_R, Line) at the County sites (A – J) from 2005 to 2007 in Nebraska. No ET_R values were recorded at Hayes and Gosper Co. sites by the Nebraska Automatic Weather Data Network.

Table 3.2. Average ratio of reference evapotranspiration (ET_R) to precipitation and maximum air temperature (T_{max}) at different physiological growth stages of grain sorghum for 10 site-years across Nebraska from 2005 to 2007

	Physiological growth stages									
Days after planting	0 - 40	40 – 65	65 – 85	85 – 120		0 - 40	40 – 65	65 – 85	85 – 120	
Growth Stage	Vegetative	Flower	Grain fill	Maturity	Avg.	Vegetative	Flower	Grain fill	Maturity	Avg.
County	[†]ET_R/Precipitation					T_{max} (°C)				
Clay 2005	3.03	3.26	5.82	2.17	2.82	28.6	32.5	30.1	28.2	29.8
Clay 2006	3.96	1.62	2.29	1.12	2.25	30.3	32.1	29.8	24.1	29.1
Clay 2007	2.74	2.59	2.62	2.05	2.11	29.9	32.8	29.2	23.9	28.9
Cheyenne 2006	2.92	35.50	6.60	2.52	11.89	30.3	33.7	29.3	21.8	28.7
Cheyenne 2007	6.72	5.33	1.05	11.92	7.40	29.9	32.8	29.2	23.9	30.2
Frontier 2006	4.18	4.48	2.38	2.59	3.41	27.1	28.9	27.8	20.7	26.1
Lincoln 2007	3.14	5.68	2.36	16.35	6.88	30.1	30.9	32.5	27.6	30.3
Red Willow 2007	3.72	1.22	3.94	2.31	2.80	28.0	31.1	31.6	32.5	30.8

[†]ET_R –Reference evapotranspiration using alfalfa as reference crop. No ET_R values at Hayes and Gosper Co. sites Nebraska Automatic Weather Data Network.

3.6.2 Soil water content at Clay County in 2005

At the Clay Co site in 2005, row configuration x plant population interaction resulted in marginal differences in soil water content at each depth throughout the season. Soil water content (SWC) ranged from 0.10 to 0.35 m^3 m^{-3} in the 0 – 300 mm depth, 0.28 to 0.45 m^3 m^{-3} in the 300 – 600 mm depth, 0.23 to 0.38 m^{-3} in the 600 – 900 mm depth and from 0.21 to 0.35 m^3 m^{-3} in the 900 – 1200 mm depth (Fig. 3.2). Soil water content at each depth decreased progressively as the crop matured. At each depth soil water content s2 was higher than with s0 treatments. The decline in SWC observed with s2 in the first half of the growing season in the top 300 mm depth may be attributed to evaporation from the exposed inter-row area with no vegetation cover. Though evaporation has been expressed as a major concern in skip-row planting, residue cover in the inter-row area and no tillage practices minimizes evaporative loss of stored soil water for the benefit of the crop use (Good and Smika, 1978; Smika, 1983). At physiological maturity, available soil water was depleted with s0 in the 0 -300 and 900 – 1200 mm depth while s2 had residual available soil water.

With adequate soil water from in-season precipitation, the low plant population produced tillers to compensate for the low plant populations, hence approximately equal amounts of soil water were extracted by both plant populations. At physiological maturity, differences in residual soil water between s0 and s2 was not significant reflecting the ability of the crop to extract stored soil water from the inter-row area.

3.6.3 Soil water content in 2006

There were no differences in stored soil water between the three row configurations in the 300 mm depth at 30 DAP at any of the sites (Figs. 3.3 and 3.4; See also Appendices 8, 9 and 10). The Hayes and Frontier Co. sites had the lowest stored soil water in the top 300 mm depth with values ranging between 0.23 and 0.28 $m^3 m^{-3}$. Soil water content was higher at Clay, Gosper and Cheyenne Co. sites with values between 0.30 and 0.38 $m^3 m^{-3}$. Fluctuation in soil water content in the top 300 mm depth at 30 DAP may be attributed to in-season precipitation, evaporation from the inter-row non-vegetated area and root extraction by the crop.

As the growing season progressed differences between the row configurations in soil water content at the 600 and 900 mm depth became more distinct at the Frontier and Cheyenne Co. sites (Figs. 3.3 and 3.4). These differences could be attributed to plant water extraction which was more intense in the s0 than the skip-row configurations. At physiological maturity, residual soil water was lowest in the s0 configuration compared with the skip-row configurations at all sites. In 2006, there was markedly more stored soil water in the s2 configuration in the 750 mm depth at Cheyenne and Frontier Co. sites than at Hayes and Gosper Co. sites at 40 to 80 DAP (Fig. 3.5).

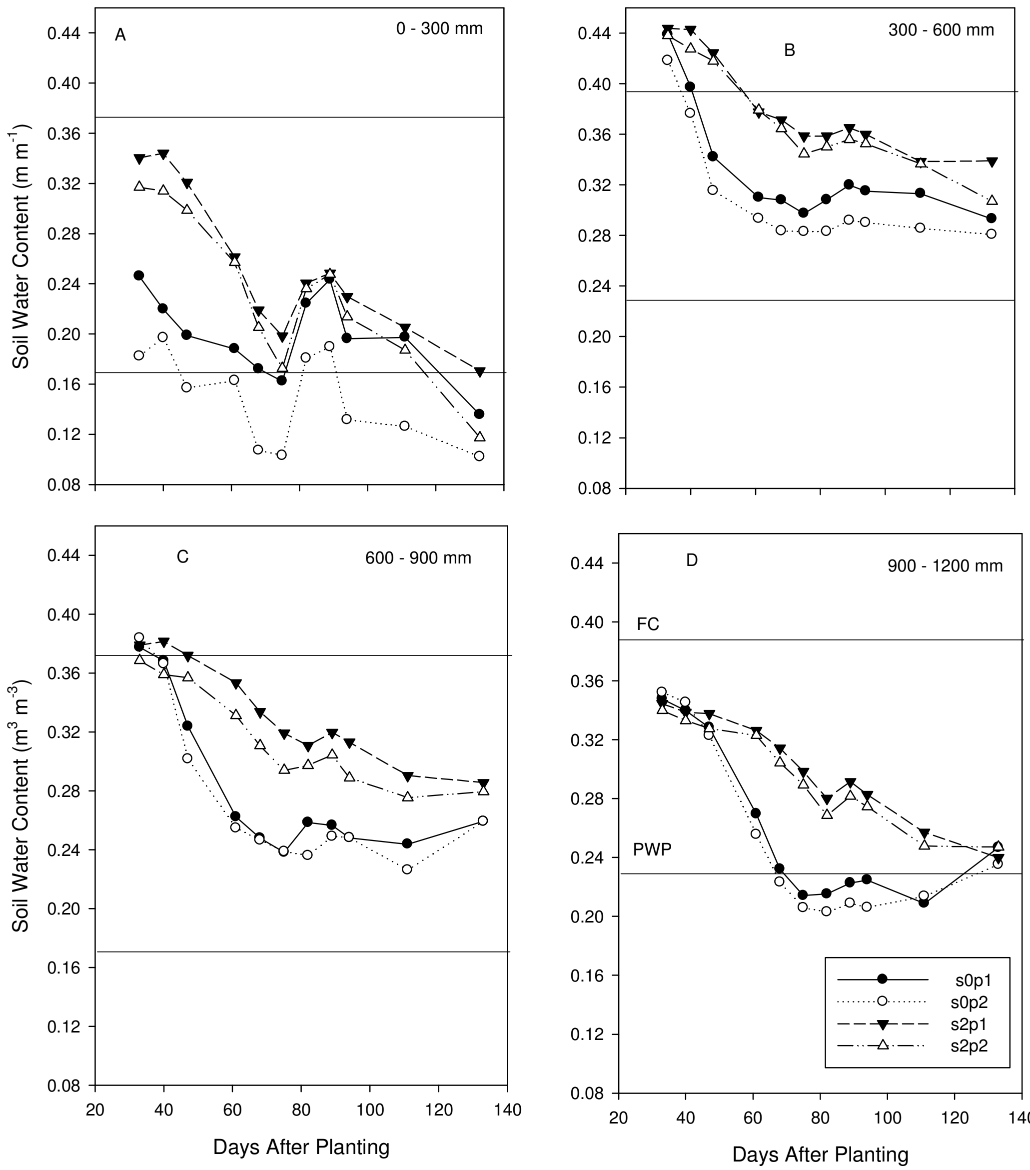


Figure 3.2. Soil water content at the mid-point of the inter-row area measured weekly at four depths as influenced by three row configurations and two plant populations at Clay Co. in 2005. s0 = conventional planting with all rows planted, s2 = two rows planted alternate with two rows skipped, p1 = 75000 plants ha^{-1}, p2 = 150000plants ha^{-1}. Upper horizontal line = field capacity (FC), Lower horizontal line = permanent wilting point (PWP). Y bars = LSD at 0.05.

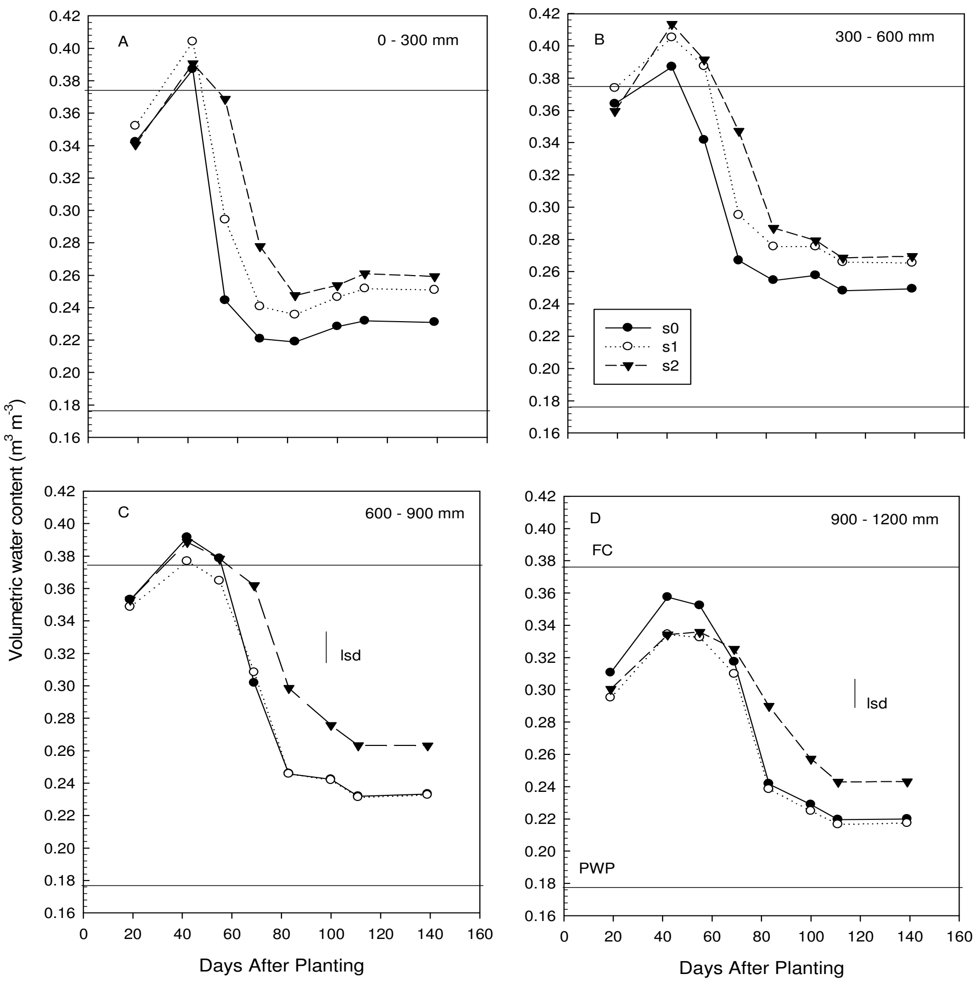


Figure 3.3. Soil water content at the mid-point of the inter-row area measured weekly at four depths as influenced by three row configurations at Cheyenne Co. in 2006. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped. Upper horizontal line = field capacity (FC), lower horizontal line = permanent wilting point (PWP). Y bars = LSD at 0.05.

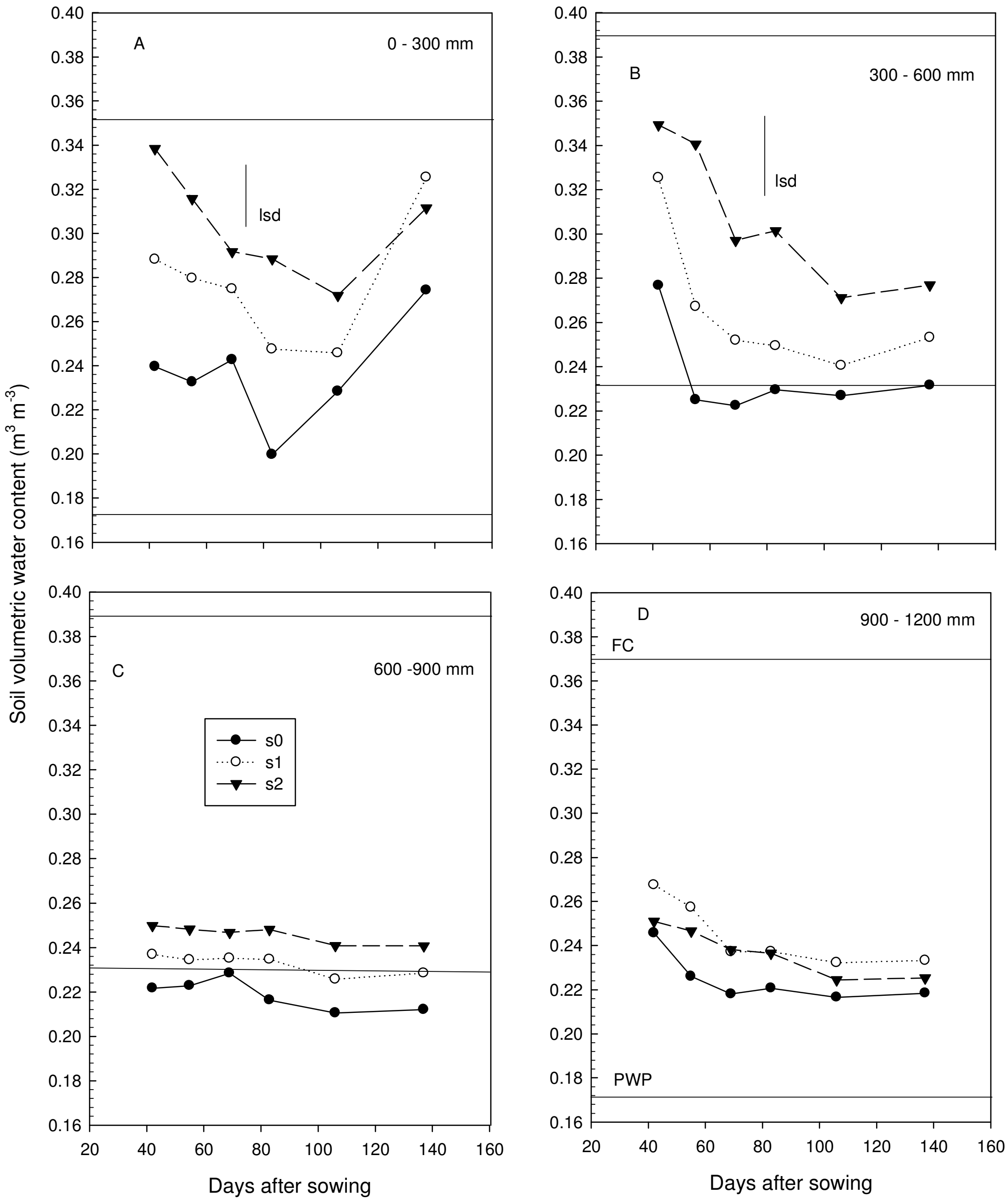


Figure 3.4. Soil water content at the mid-point of the inter-row area measured weekly at four depths as influenced by three row configurations at Frontier Co. in 2006. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped. Upper horizontal line = field capacity (FC), lower horizontal line = permanent wilting point (PWP). Y bars = LSD at 0.05.

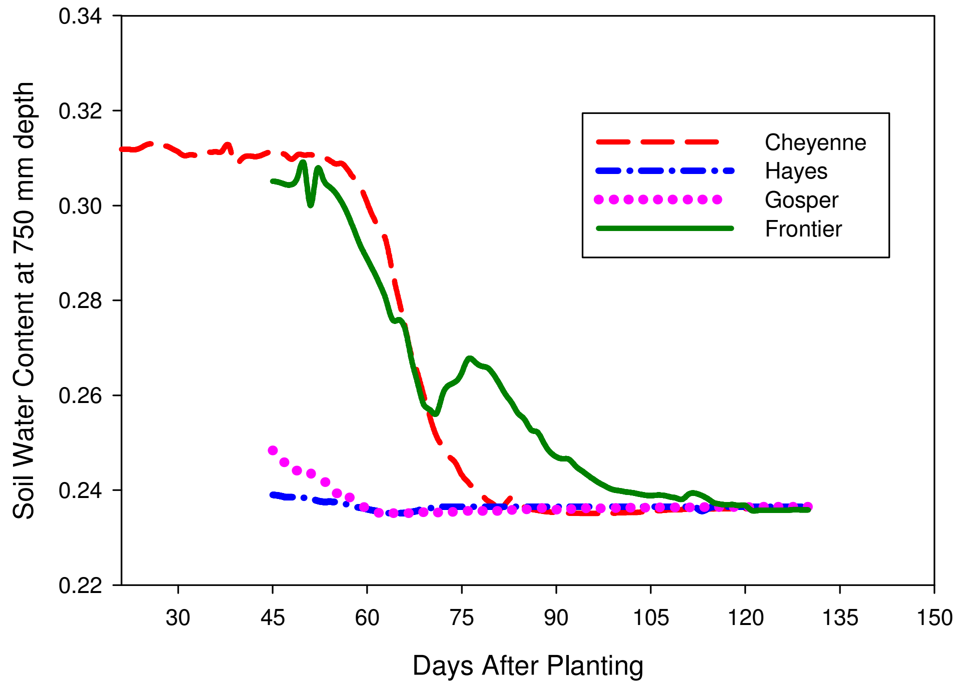


Figure 3.5. Soil water content using Watermark sensors at 750-mm depth at the mid-point of the inter-row area measured at 30 minutes interval during the growing season at four sites in Nebraska. The results presented are for plant two skip two configuration of soil water content for four sites in 2006.

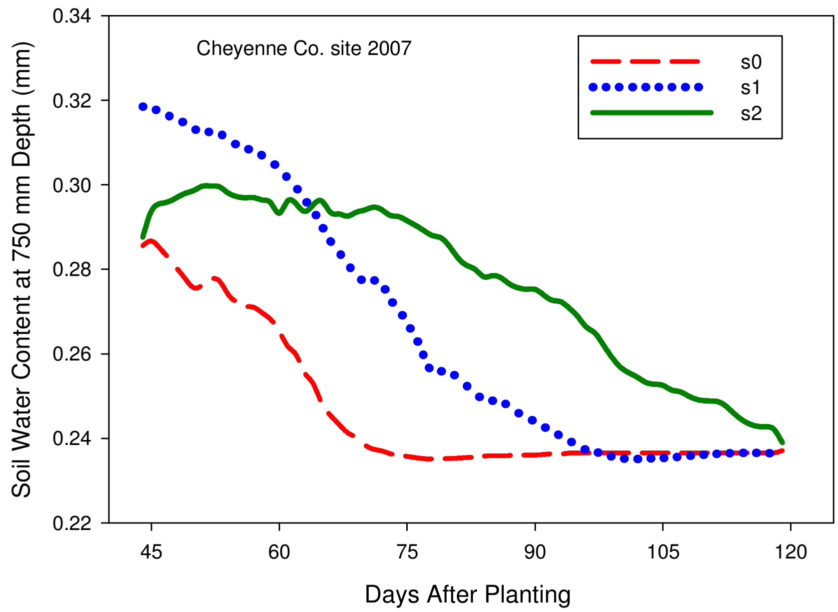
3.6.4 Soil water content in 2007

In 2007, high in-season precipitation across the four county sites (Clay, Lincoln, Red Willow and Cheyenne) resulted in no differences in SWC between the three row configurations during the growing season. At the Clay Co. site soil water content in the 1200 mm depth profile remained high during the season, ranging between 408 and 430 mm which was higher than the two previous years.

Decreases in soil water in the three planting configurations at the Lincoln and Red Willow Co. sites were marginal and fairly consistent during the growing season. In-

season precipitation was higher at Red Willow than at Lincoln Co. and soil water content was higher at the Red Willow Co. site. There was much pre-season precipitation at the Cheyenne Co. site and higher soil water throughout the growing season compared with the previous year. Soil water extraction at 750 mm depth started earlier in s0 configuration than skip-row treatment in 2007 at Clay and Cheyenne Co. sites. The s2 treatment had higher water content than s1 and s0 configuration throughout the growing season (Fig. 3.6). Uniform spacing allows the plant root the shortest time to exploit soil water between plants. When plants are crowded within a row with wide inter-row spaces, there is intense competition for water near the row but water within the inter-row area of the skip-row planting is not reached by roots until later in the season and its use occurs over a longer period of time. Thus soil water was stored early in the growing season and used by the crop later with the s1 and s2 configurations.

There were no differences in soil water content between the high and low plant populations at all sites and in all three years. Since grain sorghum has the capacity to tiller, lower plant populations were compensated by having similar number of panicles m^{-2} compared with the high population, thus subjecting both populations to similar soil water demand (Larson and Vanderlip, 1994; Conley et al., 2005).



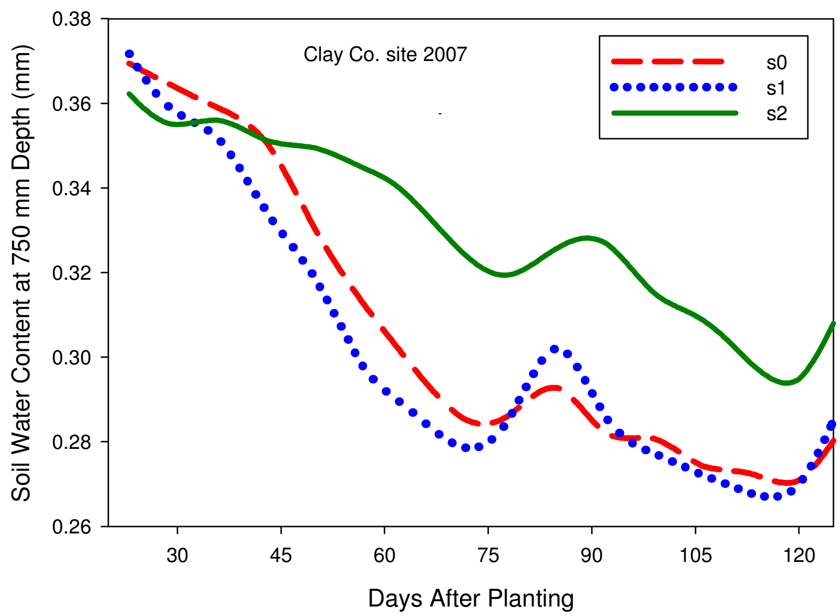


Figure 3.6. Soil water content using Watermark sensors at 750-mm depth at the mid-point of the inter-row area measured at 30 minutes interval during the growing season at the Cheyenne and Clay county sites in 2007. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped.

3.6.5 Soil water distribution and pattern

Across sites, soil water content measured at 42 DAP with s1 and s2 was generally higher than with s0 at each depth. At vegetative growth stages, soil water extraction was observed mainly in the top 300 to 600 mm (Figs. 3.7A, B, C and D). Generally, differences among the three row configurations were more distinct at reproductive growth stages where soil water with s2 was significantly higher than with s0 across sites (Figs. 3.7E, F, and G; see also Figs 3B - D). Evenly distributed root mass with s0 resulted in higher soil water extraction while the root extraction front was yet to extend into the stored soil water in the inter-row area of skip-row configurations. As the season progressed, the root extraction front extended laterally into the inter-row area and to deeper depths. At physiological maturity, available soil water at 600 – 1200 mm was depleted at the Gosper, Hayes, Frontier and Lincoln sites and there were no differences in residual soil water content between the row configurations (Figs. 3.7B, F, J and Figure 3F).

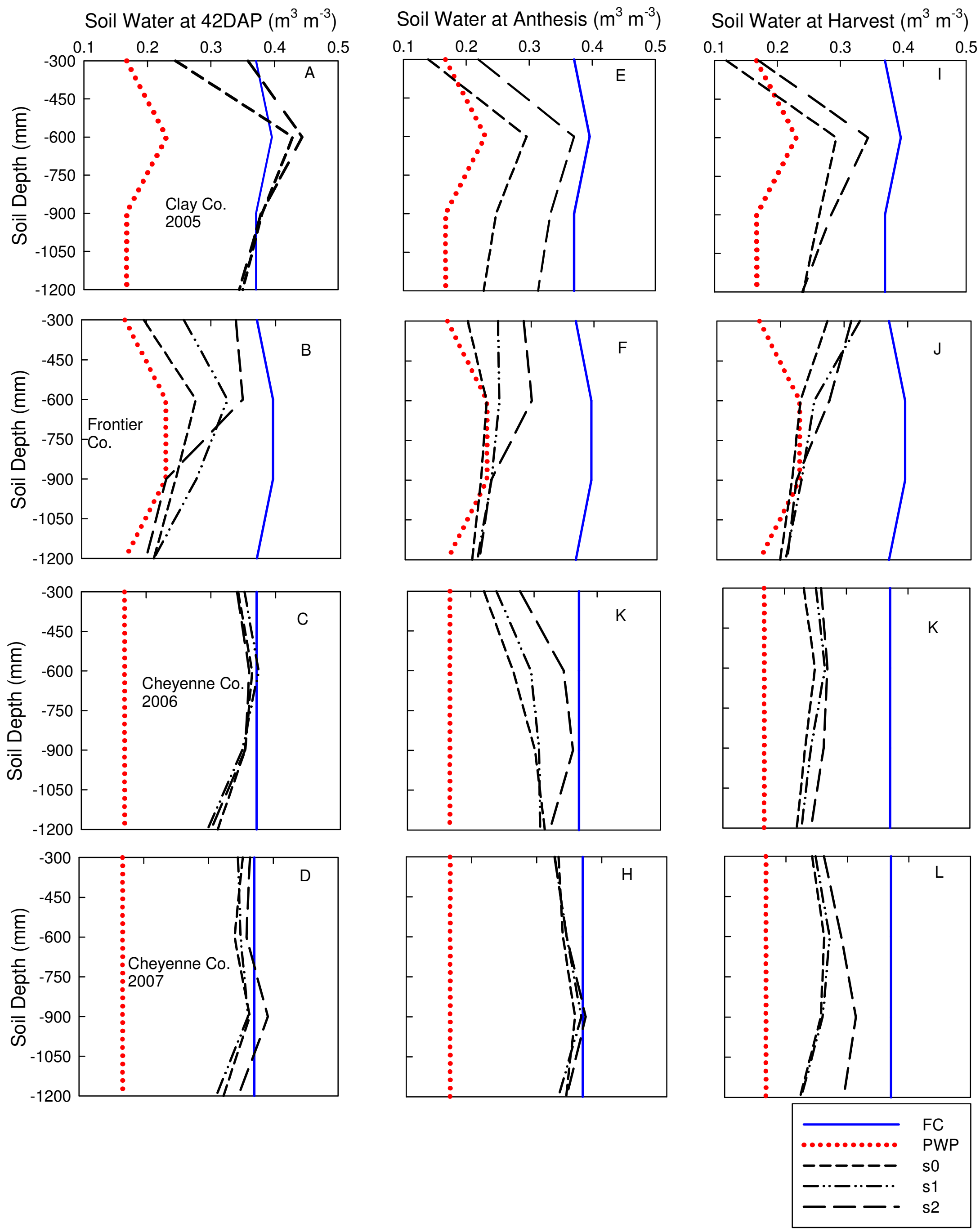


Figure 3.7. Soil water content in a profile with three row configurations for four site-years in Nebraska at 42 days after planting, at anthesis and at harvest. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted with two rows skipped. FC = Field capacity, PWP = Permanent wilting point.

3.6.6 Soil water depletion and soil water at harvest

Residual soil water (profile soil water after harvest) at the Clay Co. site (Figs. 3.8A, B and C) ranged from 234 to 253 mm in 2005, 313 to 325 in 2006 and 380 to 390 mm in 2007. Differences in residual soil water content with row configurations were significant only in 2005 when there was relatively low in-season precipitation compared to that of 2006 and 2007. Total extracted water with row configuration ranged from 354 to 531 mm (bottom stack) across years. At moderate precipitation sites (Frontier and Lincoln Co.), residual soil water in the skip-row configuration was higher than s0 configuration (Figs. 3.8D and I) but equal at Gosper and Red Willow Co. sites (Figs. 3.8E and J). Total extracted water ranged from 376 to 401 mm at the Frontier Co. site, 523 to 538 mm at Gosper Co. site, 504 to 556 mm at Red Willow Co. site and, 415 to 420 mm at Lincoln Co. site. At low precipitation sites (Hayes and Cheyenne Co.), depleted soil water ranged from 342 to 425 m (Figs. 3.8F, G and H). Skip-row configuration improved residual water content at the Cheyenne Co. site in both years but not at the Hayes Co. site. The ability of grain sorghum crop to exploit water deep into the soil profile ensures its ability to survive under water stress conditions (Jones and Johnson, 1983; Shackel and Hall, 1984). This however, may result in low residual soil water which may be an increased risk of water deficit for the subsequent crop. In contrast to the results in this study, Routley et al. (2006) reported a 16 – 26% less residual soil water content in wide (100 cm) row spacing than in 50 cm row spacing. They attributed this observation to low residue cover in the inter-row area. Without good residue cover and soils with good water holding capacity, the exposed inter-row area will be subjected to high evaporative demands and the soil will loose the store water to drainage.

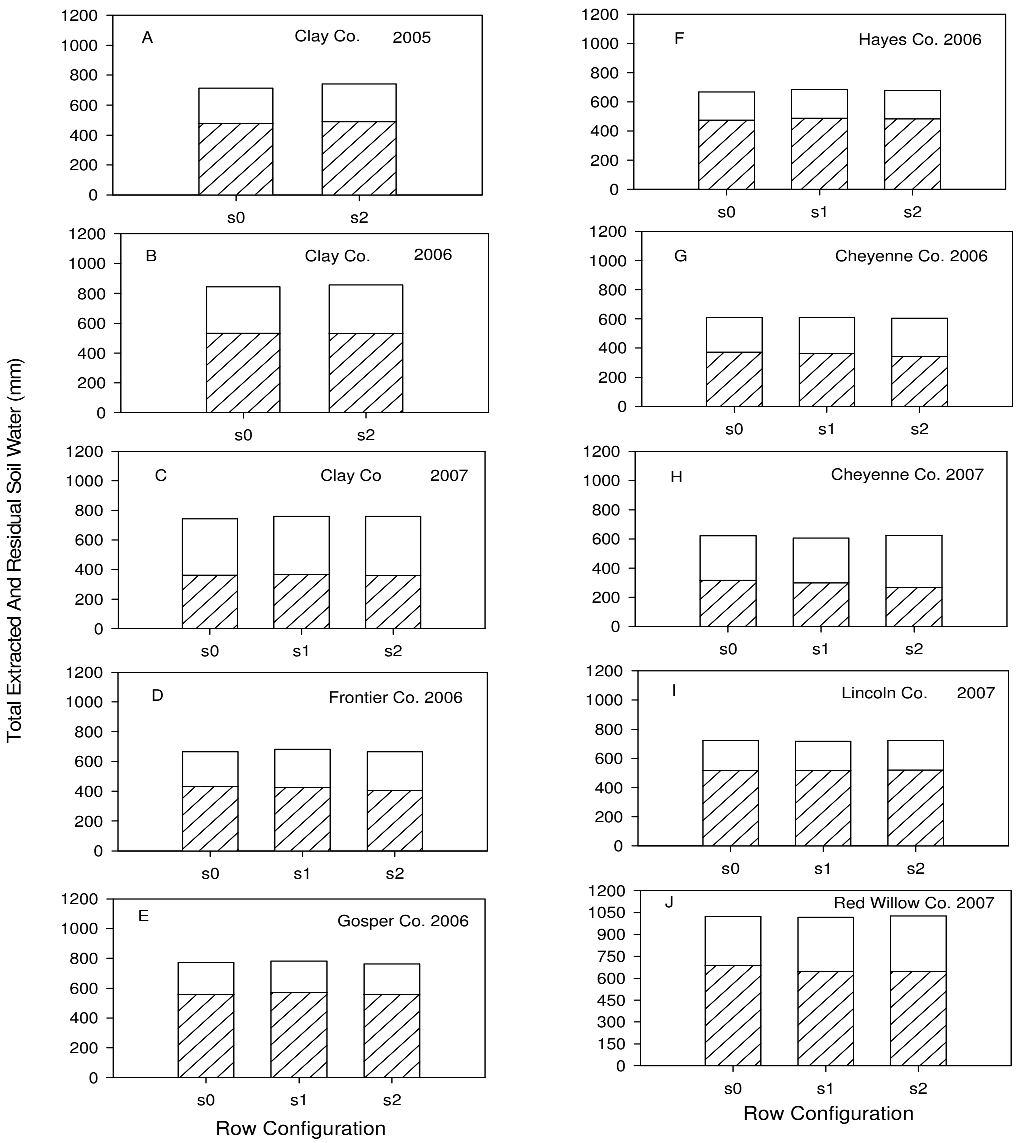


Figure 3.8. Total extracted water (bottom stack), and residual water at harvest (top stack) to a 1200 mm depth with three row configurations at 10 site-years in Nebraska. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted with two rows skipped.

3.6.7 Crop water use and water use efficiency at anthesis

Crop water use (CWU) at anthesis was significantly influenced by row configuration x plant population interactions at three out of the 10 site-years: the Frontier, Cheyenne and Lincoln Co. sites in 2007 (Table 3.3). At the Gosper, Lincoln and Red Willow Co. sites, water use efficiency (WUE) at anthesis was affected by row configuration x plant population interaction (Table 3.4). Crop water use was significantly higher with s0 than with skip-row configurations in four out of 10 site-years (Fig. 3.9). With high in-season precipitation in 2007, only the Lincoln Co. site had higher crop water use with s1 than s2.

At the Clay Co. site water use efficiency (WUE) at anthesis ranged from 20 to 29 in 2005, 20 to 24 in 2006, and 14 to 61 kg ha^{-1} mm^{-1} in 2007 (Figs. 3.9C and D). In 2007, high in-season precipitation ensured adequate soil water availability with s0. With s0, a high proportion of the available soil water was under-utilized for grain yield resulting in the lowest WUE across years. Early stages of growth in 2006 had low in-season precipitation (14 mm $week^{-1}$) compared with that of 2005 and 2007 (16 and 17 mm $week^{-1}$). This may have resulted in water deficit especially with s0 which may have caused lower WUE compared to 2005 and 2007.

Water use efficiency with s0 was higher than with s1 and s2 at all sites in 2006 exception that of the Clay and Cheyenne Co. sites (Figs. 3.9C and D). This suggests that soil water was adequate to ensure efficient utilization for vegetative biomass production with s0 until anthesis. An early dry period at the Cheyenne Co. site in 2006 coupled with high air temperature (Table 3.2) resulted in low CWU and marginal differences in WUE

among the three row configurations. Less water stress in 2007 ensured higher WUE during vegetative stages with s0 compared with s1 and s2 at all sites (Fig. 3.9D).

Table 3.3. Summary of analysis of variance of crop water use (mm) at anthesis of grain sorghum with three row configurations and two seeding rates at ten site-years.

		Clay 2005	Clay 2006	Clay 2007	Gosper 2006	Frontier 2006	Hayes 2006	Cheyenne 2006	Cheyenne 2007	Lincoln 2007	Red W. 2007
Source	DF	----------	----------	----------	----------	Mean square	----------	----------	----------	----------	----------
Row Config. (RC)	2	9229**	3703.1**	91.6ns	570.6ns	1436.3**	968.5*	1918.2**	3960.3ns	486.9**	4224**
Plant Pop (PP)	1	0.23ns	12.11ns	29.5ns	1482ns	11.08ns	174.4ns	170.4ns	61.60ns	30ns	19.3ns
RC*PP	2	186ns	47.9ns	636.8ns	136.6ns	383.3*	300.7ns	60.05ns	8792.9*	3311.9**	687ns
Residual	15†	1982	219.3	2726.7	745.3	104.2	190.2	42.78	2101.9	39.3	578.3

† Residual DF at the Clay county site in 2006 and 2007 = 46, remaining site-years = 15

* P ≤ 0.05, ** P < 0.01; ns = not significant at P = 0.05.

Table 3.4. Summary of analysis of variance of water use efficiency (kg ha^{-1} mm^{-1}) at anthesis of grain sorghum with three row configurations and two seeding rates at ten site-years.

		Clay 2005	Clay 2006	Clay 2007	Gosper 2006	Frontier 2006	Hayes 2006	Cheyenne 2006	Cheyenne 2007	Lincoln 2007	Red W. 2007
Source	DF	----------	----------	----------	----------	Mean square	----------	----------	----------	----------	----------
Row Config. (RC)	2	320.6**	72.02**	5445.3**	29.30*	1109.7**	137.7*	207.5ns	10241**	4381.9**	2626.6**
Plant Pop (PP)	1	38.25**	29.29ns	22.47ns	91.30**	98.8ns	0.245ns	11.86ns	1464.3*	57.12ns	0.383ns
RC*PP	2	10.33ns	8.24ns	58.6ns	31.54**	20.3ns	10.58ns	130.7ns	931.1ns	440.7**	152.3*
Residual	15†	8.18	5.77	76.2	8.74	61.9	26.79	80.60	291.6	48.41	34.45

† Residual DF at the Clay county site in 2006 and 2007 = 46, remaining site-years = 15

P ≤ 0.05, ** P < 0.01; ns = not significant at P = 0.05.

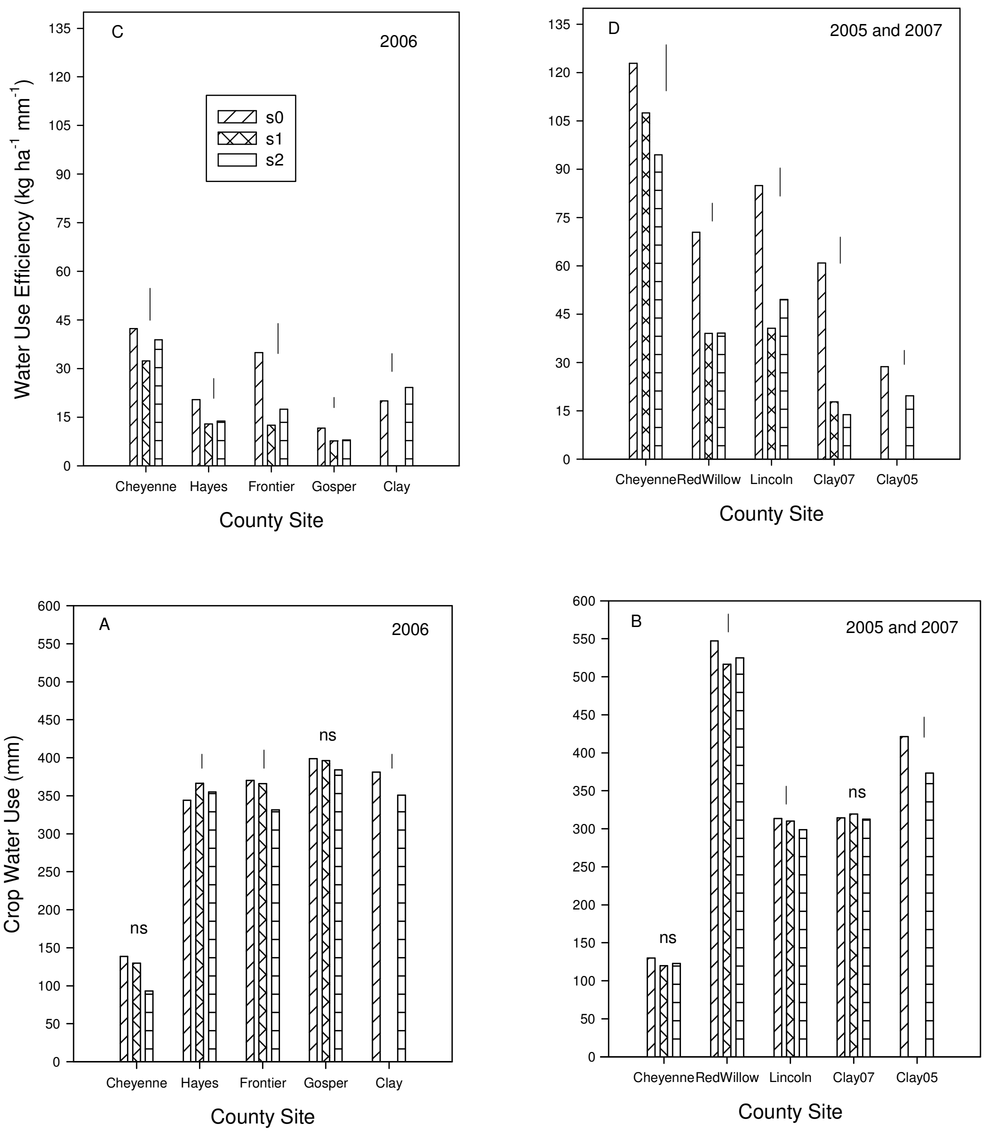


Figure 3.9. Effect of three row configurations on crop water use (A and B) and water use efficiency (C and D) of grain sorghum at anthesis for 10 site-years across Nebraska. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted with two rows skipped. Y-bars = LSD 0.05 within site-years, ns = not significant.

3.6.8 Crop water use and water use efficiency at physiological maturity

Row configuration x plant population interaction influenced CWU at maturity at two out of the 10 site-years, while row configuration influenced three out of the 10 site-years (Table 3.5). At Cheyenne and Frontier Co. sites, CWU was in order of s0>s1>s2. At the Red Willow Co. site, CWU with s0 was significantly higher than the skip-row configurations, but the difference between s1 and s2 was not significant (Figs. 3.10A and B).

Row configuration x plant population interaction resulted in significant differences in WUE at only the Lincoln and Red Willow Co. sites (Table 3.6). Water use efficiency with s0 across sites ranged from 2.3 at the Hayes Co. site to 23.3 kg ha^{-1} mm^{-1} at the Clay Co. site. With skip-row configurations, WUE ranged from 4.1 at Hayes to 18.2 kg ha^{-1} mm^{-1} at Clay Co. site with s1, and from 4.9 at Hayes to 28 kg ha^{-1} mm^{-1} at Clay Co. site with s2. Water use efficiency with skip-row configuration was higher than or equal to WUE with s0 configuration at moderate and low rainfall sites (Fig. 3.10C). At the Clay Co. site, WUE was higher with s0 in 2005 and 2007.

Improvement in WUE in drier environments with skip-row configuration could be attributed to the availability of soil water in the skipped area at reproductive stages which was subsequently utilized to increase in grain yield. Abbate et al. (2004) argued that improvement in WUE of wheat in water deficit environments is probably due to stomatal closure and reduced transpiration rate. This may have ensured adequate water for carbohydrate synthesis and partitioning in favor of grain yield. Water use efficiency was similar for s1 and s2 for all site-years except Lincoln Co. in 2007.

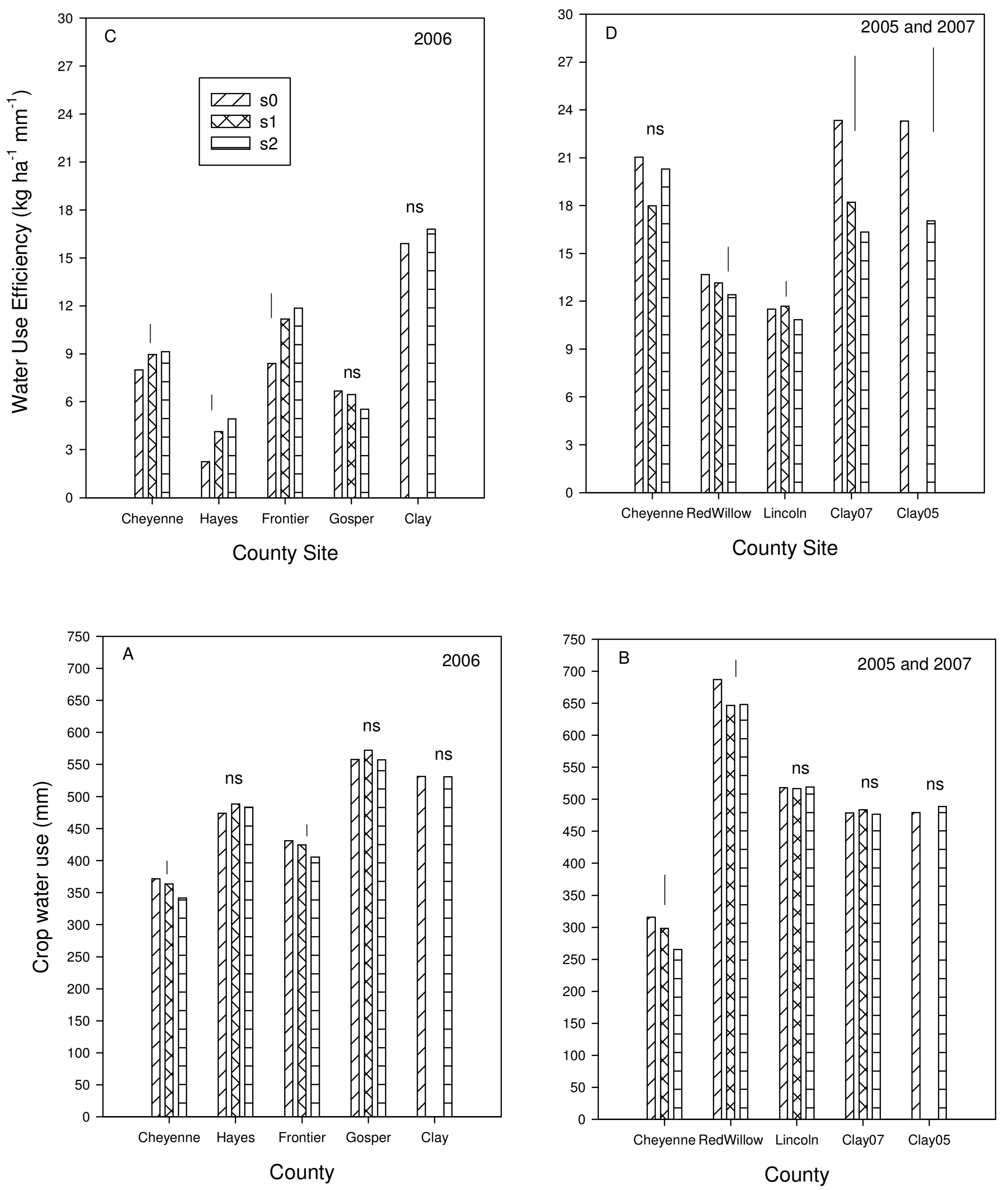


Figure 3.10. Effect of three row configurations on crop water use (A and B) and water use efficiency (C and D) of grain sorghum at physiological maturity across Nebraska. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted with two rows skipped. Y-bars = LSD 0.05 within site-years, ns = not significant.

Table 3.5. Summary of analysis of variance of crop water use (mm) at harvest of grain sorghum with three row configurations and two seeding rates at ten site-years.

		Clay 2005	Clay 2006	Clay 2007	Gosper 2006	Frontier 2006	Hayes 2006	Cheyenne 2006	Cheyenne 2007	Lincoln 2007	Red W. 2007
Source	DF	-- Mean square --									
Row Config. (RC)	2	352.3ns	0.70ns	91.6ns	570.6ns	1436.3**	448.9ns	1918.2**	5293.6ns	14.36ns	4224**
Plant Pop (PP)	1	786.5*	88.95ns	29.5ns	1182ns	11.08ns	11.8ns	170.4ns	190.9ns	135.7ns	19.3ns
RC*PP	2	378.4ns	204.6ns	636.8ns	136.6ns	383.3*	77.7ns	60.05ns	8970.6ns	835.9**	687ns
Residual	15†	138	412.8	2726.7	745.3	104.2	166.5	42.78	2748.2	92.13	578.3

† Residual DF at the Clay county site in 2006 and 2007 = 46, remaining site-years = 15

P ≤ 0.05, ** P < 0.01; ns = not significant at P = 0.05.

Table 3.6. Summary of analysis of variance of water use efficiency (kg ha^{-1} mm^{-1}) at harvest of grain sorghum with three row configurations and two seeding rates at ten site-years.

		Clay 2005	Clay 2006	Clay 2007	Gosper 2006	Frontier 2006	Hayes 2006	Cheyenne 2006	Cheyenne 2007	Lincoln 2007	Red W. 2007
Source	DF	---- Mean square ----									
Row Config. (RC)	2	156.3*	3.35ns	105.3**	2.97ns	26.96**	15.17**	2.94**	3.51ns	3.22ns	1.57*
Plant Pop (PP)	1	0.156ns	30.03**	7.20ns	3.63ns	5.60ns	1.74ns	12.04**	0.065ns	0.345	0.13ns
RC*PP	2	1.315ns	10.22ns	1.24ns	0.70ns	1.80ns	1.98ns	0.23ns	105.1ns	11.14**	11.75**
Residual	15†	18.94	2.12	10.8	7.19	3.07	0.77	0.25	39.97	1.14	0.27

† Residual DF at the Clay county site in 2006 and 2007 = 46, remaining site-years = 15

P ≤ 0.05, ** P < 0.01; ns = not significant at P = 0.05

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. The relationship between ratios of CWU to maximum CWU (CWU/CWU_{max}) and grain yield to maximum grain yield (Y/Y_{max}) was linear with each row configuration with coefficients of determination of 0.84, 0.76 and 0.84 with s0, s1, and s2, respectively (Fig. 3.11). This suggests that for any given CWU there is a linear association with an approximate grain yield across sites.

There was a linear relationship between crop water use and total dry matter yield (stover plus grain) at harvest with the s0 configuration, with a significant coefficient of determination of 92% (Fig. 3.12). On the other hand a curvilinear relationship was found between CWU and skip-row configurations with coefficient of determination of 91 and 83% with s1 and s2 configurations, respectively. Wider spacing skip-row configuration is likely to have higher soil evaporation and under-utilization of radiation and soil nutrients due to low plant coverage compared to conventional planting. The more curvilinear relationship with the s2 suggests that available soil water exceeded the maximum crop water requirement for this configuration averaged over sites.

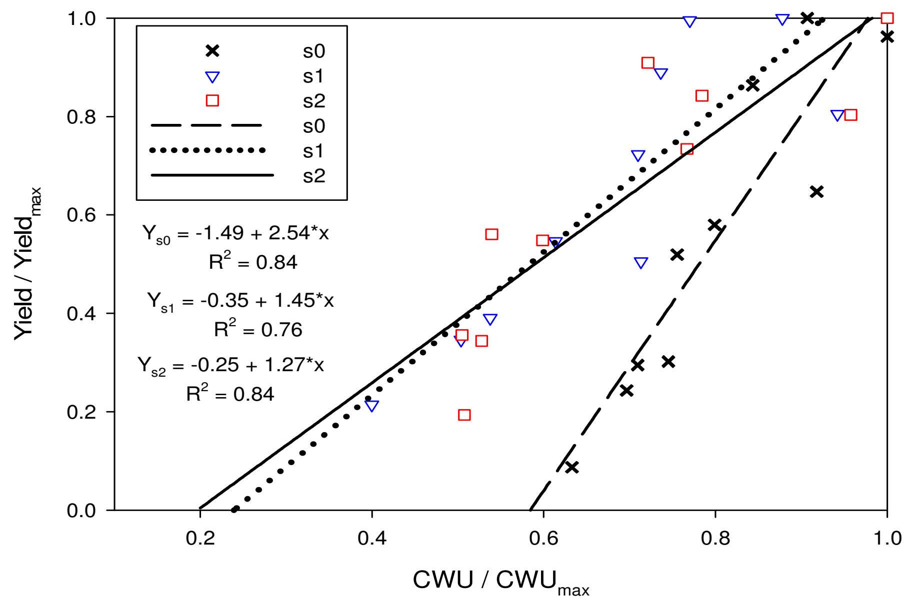


Figure 3.11. Ratio of crop water use (CWU) to maximum CWU (CWU/CWU_{max}) and grain yield to maximum grain yield (Y/Y_{max}) of three row configurations across 10 site-years in Nebraska. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted with two rows skipped.

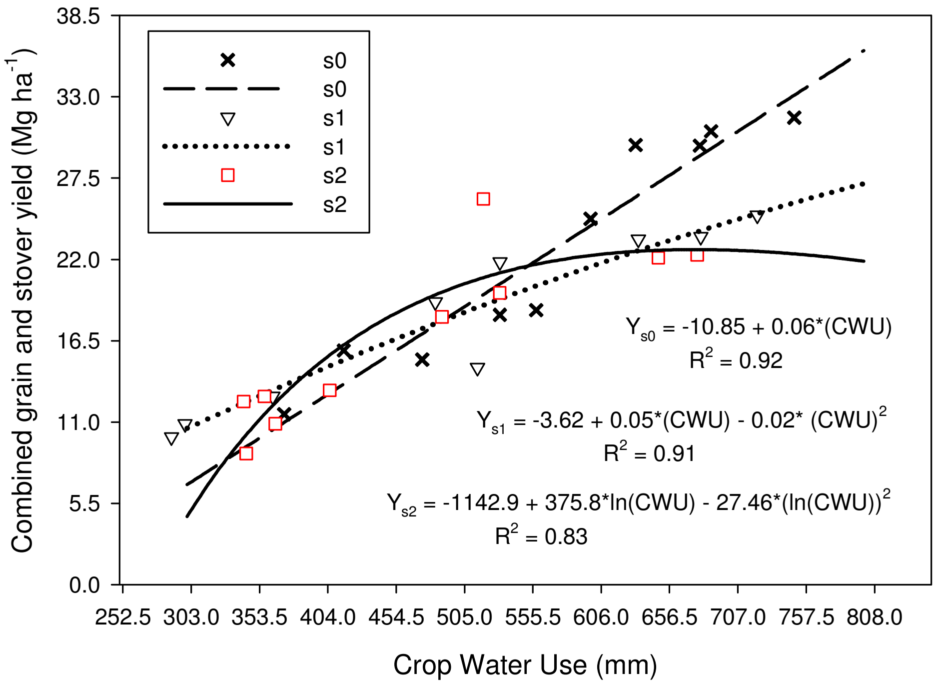


Figure 3.12. Relationship between crop water use (CWU) and total crop yield at physiological maturity with three row configurations across 10 site-years in Nebraska from 2005 to 2007. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted with two rows skipped.

3.7 Conclusions

Water stress during the grain fill and/or flower stage reduced total grain yield even when total in-season precipitation was high. The pattern of distribution of in-season precipitation and soil water content affected crop water use and water use efficiency across sites. With little or no water deficit, grain yield and WUE were less with skip-row configurations compared to s0. Grain yield and WUE were similar with s0 and with skip-row configurations in moderate rainfall environment. In severe water deficit environment, grain yield and WUE with skip-row configurations were higher than with conventional planting.

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CHAPTER FOUR

EFFECT OF ROW CONFIGURATION, PLANT POPULATION AND N APPLICATION ON N USE EFFICIENCY OF GRAIN SORGHUM IN SOUTH CENTRAL NEBRASKA.

4.1 Abstract

Water and N supply are often the most critical factors limiting growth and yield in crop production. A research study was carried out from 2005 to 2007 to determine nitrogen use efficiency in dryland grain sorghum (*Sorghum bicolor* (L.) Moench) production at University of Nebraska, Lincoln, Nebraska, South Central Agricultural Laboratory. The study evaluated three row configurations including all rows planted (s0), alternate rows planted (s1), and two rows planted alternated with two skipped rows (s2) in a complete factorial with two plant population densities: 75000 and 150000 seeds ha^{-1} and four N application rates of 0, 50, 100 and 150 kg N ha^{-1}. The objectives of the study were to determine the optimum N rate, N uptake and N use efficiency (NUE) for grain sorghum under dryland conditions. Conventional planting out-yielded skip-row planting in each year with no observed incidence of severe crop water stress. Nitrogen application resulted in increased grain yield with s0, however difference in grain yield at 100 and 150 kg N ha^{-1} were similar in both 2006 and 2007. Increasing rate N rate above 50 kg N ha^{-1} did not result in increased grain yield with s1 and s2. Grain sorghum response to N rate was quadratic in both years and with all row configurations. Percent N relocated from biomass at anthesis to grain at physiological maturity ranged from 29 to 35% in 2006 compared with 46 to 51% in 2007. Leaf chlorophyll at 65 days after planting (DAP) had

a quadratic relationship with grain yield at physiological maturity with $R^2 = 0.98$. Conventional planting (s0) had higher agronomic N use efficiency (AE_N) and partial factor productivity of applied N (PFP_N) than skip-row configurations. Application of N at 50 kg ha^{-1} gave higher AE_N and PFP_N than at 100 and 150 kg N ha^{-1} in 2006 and 2007.

4.2 Introduction

Grain sorghum is quite tolerant of soil water deficits and efficiently uses available soil nutrients due to its fibrous root system. However, sorghum yield potential can be substantially limited when water and N are inadequate. Nutrient uptake by sorghum is influenced by several factors including nutrient availability, soil water availability, soil organic matter, soil chemical and physical properties, type of previous crop, and the genotype (Wortmann et al., 2007; Gardner et al., 1994; Borrell and Hammer, 2000).

Most Nebraska producers grow sorghum under dryland conditions and lack of available water reduces yield and yield response to fertilizer (Stewart and Steiner, 1990). On the other hand, N deficiencies can reduce water use efficiency due to reduced yield potential and greater soil evaporation (DeWit, 1958; Fisher and Turner, 1979). According to Maiti (1996) total N removed by grain sorghum crop (grain plus stover) producing approximately 8000 kg ha^{-1} is 250 kg N ha^{-1}. In highly variable environments inherent in dryland cropping systems, variable mineralization of soil and organic N makes predicting optimal N fertilizer rate a challenge (Schlegel et al., 2005). Crop management system, weed control, and available soil water due to in-season precipitation results in improved N response N fertilizer application (Eck and Jones, 1990; Sow et al., 1998).

An important key component to crop production is to achieve the greatest ratio of harvested dry weight to water and/or N use, referred to as water use efficiency (WUE) and N use efficiency (NUE). Improving plant efficiency for fertilizer use is important to reduce costs of crop production, and N is one of the most costly inputs for crop production. Nitrogen use efficiency has been estimated using different indices (Dobermann 2005; Mosier et al., 2004; Cassman et al., 1998; Bock, 1984; Novoa and Loomis, 1981).

Resource use efficiency by crops is strongly influenced by climatic factors such as evapotranspiration, relative humidity and temperature which affect transpiration and assimilation (Tanner and Sinclair, 1983; Fischer, 1980; Fischer and Turner, 1979; de Wit, 1958). The difference between crop canopy temperature and temperature of the surrounding air may be an indicator of the water status of the crop (Ajayi and Olufayo, 2004). Water stress causes partial stomata closure which reduces transpiration but causes leaf temperature to increase above the ambient air temperature.

Nitrogen is the most important nutrient for optimum grain sorghum yield in Nebraska and N fertilizer recommendations for conventional planting are based on yield goals, soil organic matter level, and residual soil nitrate-N (Ferguson, 2000). To improve soil water availability and avoid water stress, skip-row configurations have been used elsewhere with success (Blum and Naveh, 1976; McLean et al., 2003; Routley et al., 2003). Different row configurations may influence plant canopy architecture, root distribution, N and water availability, uptake and utilization.

4.3 Hypotheses and objectives of study

The hypothesis of this study was that the interaction between N rate, row configuration and plant population will significantly influence grain yield, N uptake and N use efficiency. The objectives of this study were to:

i. Evaluate the effects of row configuration, N rate and plant population on sorghum grain yield and N use efficiency in a rain-fed environment.

ii. Evaluate canopy temperature and relative humidity as influenced by row configuration and plant population.

4.4 Materials and Methods

The study was conducted in 2005, 2006 and 2007 at the University of Nebraska-Lincoln, South Central Agricultural Laboratory (SCAL) near Clay Center, Nebraska (lat.40^{o}34'N; long 98^{o}08; 543 m elevation). The study evaluated three planting configurations and two plant populations with different N rates in a randomized complete block design with four replications. Row configurations included all rows planted with base 76-cm row spacing (s0) and two skip row configurations: one row planted alternated with one row skipped (s1), and two rows planted alternated with two skipped (s2).

Seeding rate and thinning after emergence was done to establish plant population of 75,000 and 150,000 plants ha^{-1}. In each year a medium (110 days) maturing grain sorghum (*Sorghum bicolor* (L.) Moench) cv. Dekalb 42-20 (Monsanto Co., USA) was planted at different sites but on the same soil series: Crete silt loam - fine, smectitic, mesic Pachic Arguistolls (USDA Natural Resources Conservation Service). In 2005 N was applied at the rate of 100 kg ha^{-1}, and four N rates of 0, 50, 100 and 150 kg N ha^{-1} were applied in

2006 and 2007. A basal rate of phosphorus was applied at 40 kg ha^{-1} to all plots. Weeds were controlled with pre-plant herbicide (Dual II Magnum + crop oil concentrate + atrazine), and post-emergence herbicide (Paramount + crop oil concentrate + atrazine) application plus hand hoeing where necessary.

SPAD-502 chlorophyll meter (Minolta Co., Osaka, Japan) readings were taken from the uppermost fully expanded 20 leaves from each plot and averaged to one value per plot. Nine SPAD-502 readings during the season were taken in 2005, four in 2006 and four in 2007. SPAD-502 readings were converted to leaf chlorophyll using an equation by Markwell et al. (1995):

Leaf chlorophyll (µmol m^{-2}) = $10^{(M\text{^}0.265)}$, where M is the SPAD-502 reading.

In-season precipitation, reference evapotranspiration (ET_R), solar radiation, wind speed, air temperature and relative humidity during the growing season and 20-year average weather data were collected from the University of Nebraska Automated Weather Data Network (AWDN) at the site. Canopy temperature and relative humidity were measured with HOBO H8 Pro Series sensors (Version 4.3, Onset Computer Co. 2002. Bourne, MA)

Above ground biomass at anthesis and physiological maturity were harvested from an area of 2.28 m^2, oven dried at 65°C for 72 hours and weighed. Grain yield was determined from 60.8 m^2 of harvested area and standardized at 135 g kg^{-1} water content. Oven-dried sub-samples of biomass and grain were analyzed for N concentration. Plant and grain N uptake were calculated by multiplying the dry weight of biomass and grain by the N concentration.

Nitrogen use efficiency was calculated using three indices used in agronomic research to assess the efficiency of applied nitrogen (Novoa and Loomis, 1981; Bock, 1984; Cassman et al., 1998; Mosier et al., 2004:

i. Partial factor of productivity (PFP), defined as total grain yield per unit N applied.

$PFP_N = Y_{grain} / N_{applied}$

ii. Agronomic N use efficiency (AE_N) also referred to as yield efficiency, defined as the increase in grain yield due to N.

$AE_N = Y_{grain\ increased} / N_{applied}$

iii. Crop recovery efficiency (RE_N) was calculated by dividing N uptake by grain by N applied

$RE_N = N_{uptake} / N_{applied}$

Where Y_{grain} is grain yield at particular N fertilizer rate, $N_{applied}$, and N_{uptake} is uptake of N by plant parts.

4.5 Statistical analysis:

All data were analyzed using analysis of variance by mixed linear model procedure (Proc Mixed, SAS Institute, 2007, Cary, NC, USA). The format of the ANOVA was a randomized complete block design with four replications. The least significant difference (LSD) was calculated when the F-test was significant $P \leq 0.05$ and used to separate treatment means. Regression analysis was performed to establish the relationship of chlorophyll content with N concentration in sorghum leaves at anthesis and grain yield at physiological maturity.

4.6 Results and Discussion

4.6.1 Initial soil analysis

In all three years, the mean soil bulk density was 1.15 g cm^{-3} in the top 0 to 300 mm depth and 1.24 g cm^{-3} in the 600 to 1200 mm depth. Each year, sorghum was sown at a site planted to corn in the previous year. The soil at the 2005 site had higher nitrate, soil organic matter, available P and exchangeable K compared to 2006 and 2007 sites (Table 4.1).

Table 4.1. Soil chemical properties of the 0 to 200 mm depth and 200 – 900 mm depth in parenthesis of the experimental sites at South Central Agricultural Laboratory, Clay County, Nebraska in 2005, 2006 and 2007

	pH	Org. matter	NO_3-N	Bray-1 P	NH4OAc. K	DTPA Zn
Year		-----%---	----------------------mg kg^{-1}	-------------------------		
2005	5.5	2.95	5.5	43.0	487.0	1.05
2006	5.9	2.68	1.73 (0.60)	27.3	383.0	1.60
2007	5.9	2.60	4.80 (2.70)	21.3	342.3	0.34

4.6.2 Effects of climate, in-season precipitation and reference evapotranspiration

During the study period, mean weather conditions were similar to the 20-year average. The excess of reference evapotranspiration (ET_R) over precipitation, referred to as climatic deficit (Olufayo et al., 1996) was highest in 2005 at flowering and grain fill stages compared to 2006 and 2007. Water deficit at flower stage will affect grain yield more than water deficit in the vegetative or grain fill stages (Stone et al., 1996). The relatively high climatic deficit observed in 2005 can be attributed to low in-season precipitation and uneven distribution of rainfall events (Fig. 4.1A). However stored soil water supplied adequate water to meet evaporative demands, thus eliminating any adverse effect of climatic deficit at the flower stage. Moreover, moderate dry periods may not affect grain yield since sorghum is noted for its ability to withstand dry conditions (Jones and Johnson, 1983; Shackel and Hall, 1984).

Total in-season precipitation in 2005 amounted to 71% of the 50-year average of 495 mm. Weekly precipitation ranged from 0 to 43 mm with the highest in-season rainfall event occurring between 60 and 65 DAP (Fig. 4.1A). Weekly total reference evapotranspiration (ET_R) was higher than weekly precipitation for most of the growing season, ranging between 23 and 66 mm. The lowest in-season precipitation during the season occurred between 20 and 60 DAP when the weekly precipitation accounted for less than 19% of the weekly ET_R.

In 2006 weekly precipitation ranged from 0 to 56 mm while weekly ET_R ranged from 24 to 62 mm. The difference between precipitation and ET_R was lowest during flower and grain fill stages (Fig. 4.1B). Weekly precipitation in 2007 (Fig. 4.1C) ranged from 1 to 60 mm and was 120% of the 50-year average. From boot to grain fill stage,

weekly precipitation either exceeded or accounted for more than 50% of the weekly ET_R making 2007 the wettest season in the 3-year study period.

Table 4.2. Mean climatic data at Clay County, Nebraska, during the 2005 to 2007 growing seasons.

Climatic data	Year	0 – 40 DAP (Vegetative)	40 - 65 DAP (Flower)	65 - 85 DAP (Grain fill)	85 - 120 DAP (Maturing)
		Physiological growth stages			
		Solar radiation (MJ day^{-1})			
	2005	21.6	23.6	17.1	17.5
	2006	23.6	22.8	18.2	15.2
	2007	23.1	22.8	17.9	14.1
20-year Avg.		22.3	21.44	18.8	15.6
		Wind speed (m sec^{-1})			
	2005	3.72	3.07	2.52	3.34
	2006	3.44	2.95	2.65	3.17
	2007	3.34	3.03	2.60	3.42
20-year Avg.		3.59	2.81	2.77	3.22
		Soil temperature (^{o}C)			
	2005	23.7	27.5	24.8	22.7
	2006	25.6	27.4	24.9	18.6
	2007	25.6	27.4	24.2	18.1
20-year Avg.		23.7	26.3	24.9	20.0
		Relative Humidity (%)			
	2005	68.9	64.9	81.5	66.8
	2006	63.0	70.0	81.2	71.1
	2007	65.1	69.8	80.6	69.0
20-year Avg.		70.3	74.9	76.4	67.5
		Air temperature (^{o}C)			
	2005	28.6	32.3	28.6	28.4
	2006	30.3	31.9	28.5	23.4
	2007	29.9	32.4	27.0	23.8
20-year Avg.		27.7	28.9	28.7	25.0
		Climatic deficit (mm)			
	2005	-196	-117	-32	-159
	2006	-207	-106	2	-78
	2007	-164	-107	-19	-84
20-year Avg.		-122	-96	-68	-85

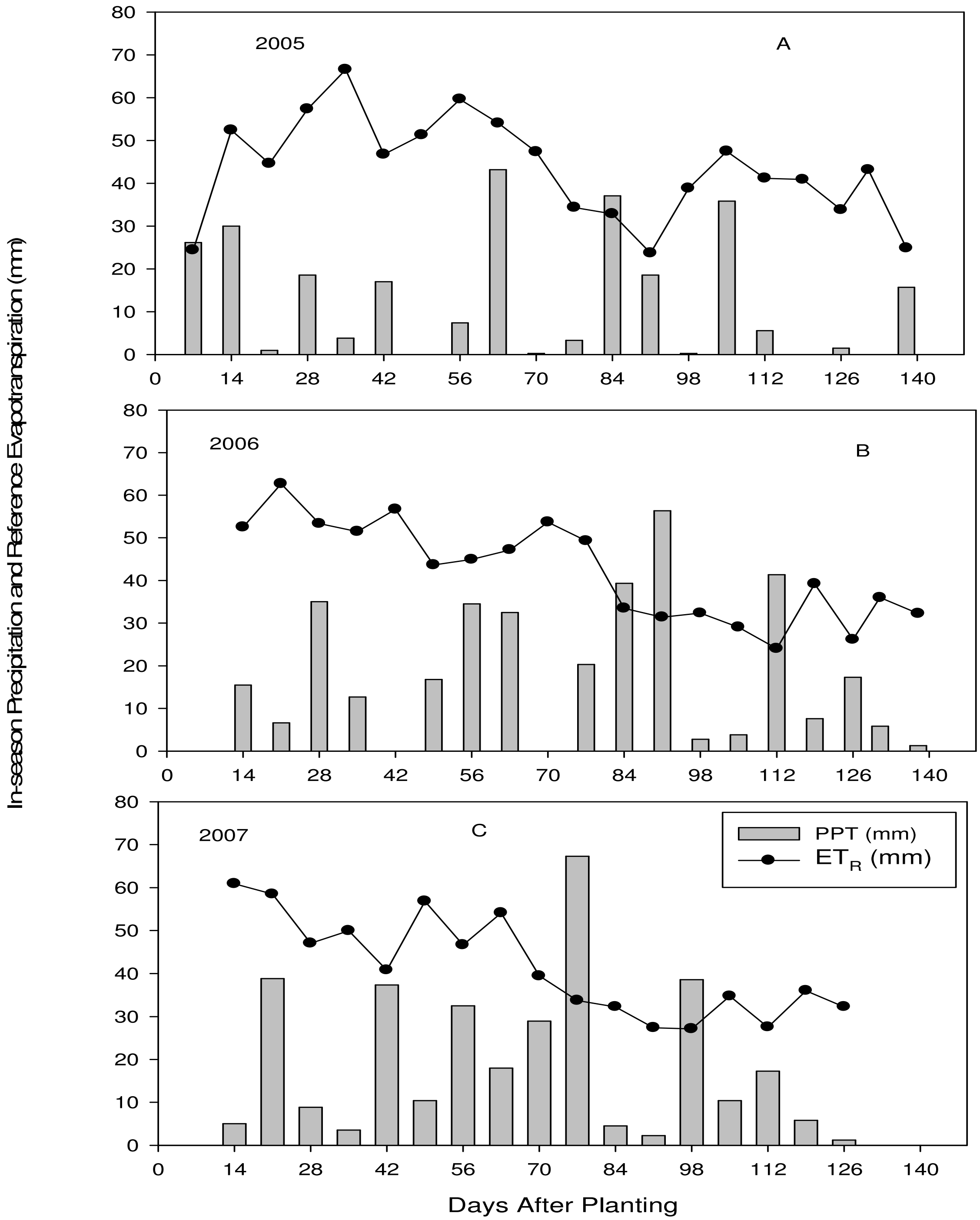

Figure 4.1. Weekly precipitation (bar) and alfalfa reference evapotranspiration (ET_R, line) at the Clay County, Nebraska, from 2005 to 2007.

4.6.3 Effect of row configuration on canopy temperature and relative humidity

Row configuration did not affect canopy temperature (Tc) in either 2006 or 2007 (Figs. 4.2 and 4.3). In late vegetative and early flower stages in 2006, air temperature (Ta) was marginally lower than Tc. However, Ta was 0.5 to 3 ^{o}C higher than Tc after flowering stage until physiological maturity in 2006 and during the entire growing season in 2007 (Figs. 4.2A and 4.3A). In both 2006 and 2007, canopy relative humidity (RHc) was not influenced significantly by the row configurations. However, RHc was higher than air relative humidity (RHa) during the growing season (Figs. 4.2B and 4.3B). This observation implied that there was adequate water to support transpiration, avoid water deficit stress and kept canopy temperature lower than ambient temperature (Jackson et al., 1981; Gardner et al., 1981; Diaz et al., 1983). In studies on irrigated and non-irrigated sorghum, Olufayo et al. (1996) observed that the difference between Tc and Ta increased to a maximum of 7^{o}C for stressed sorghum from 48 DAP to 80 DAP while the difference was close to zero over the same period with irrigation.

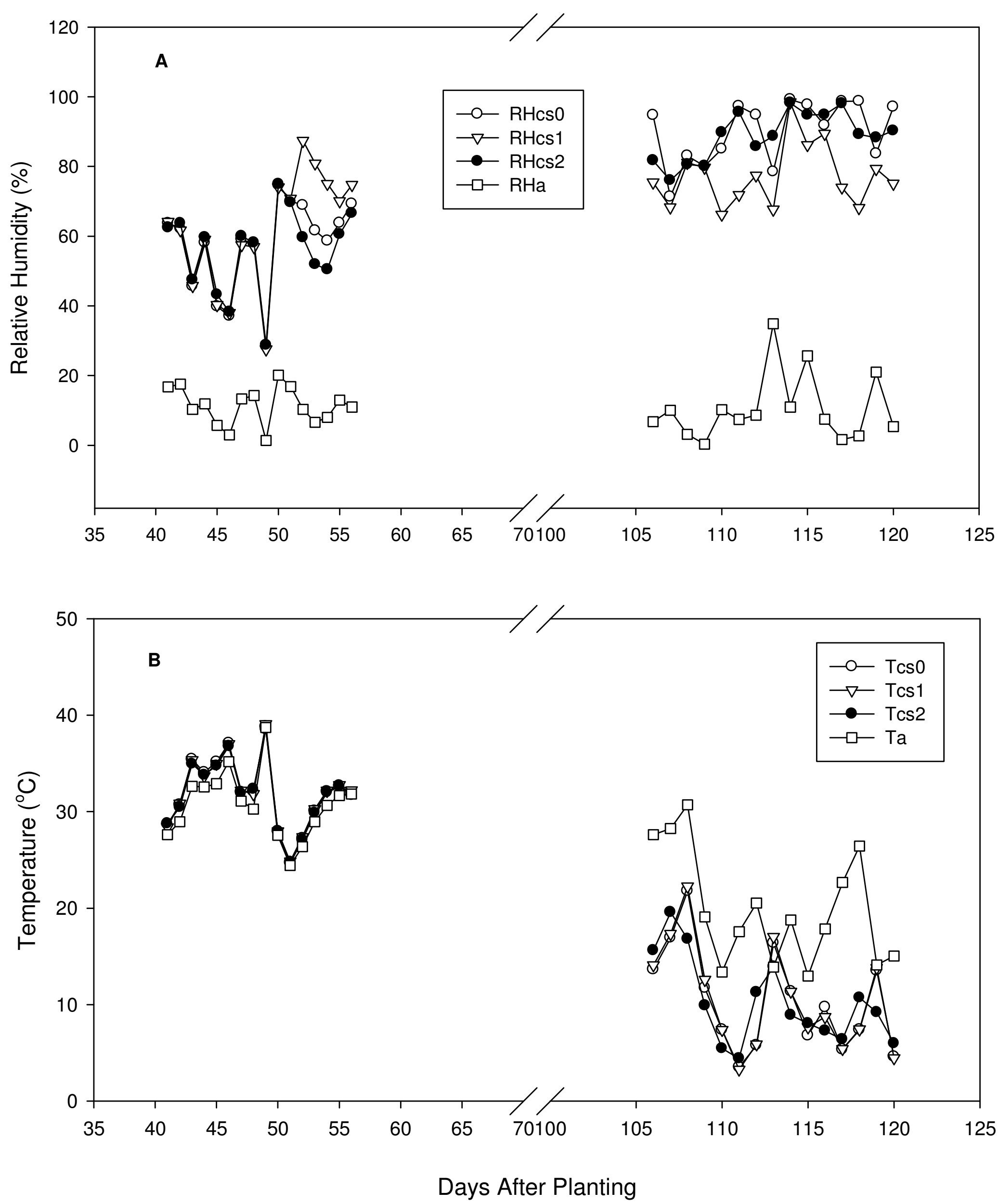

Figure 4.2. Relative humidity of air (RHa) and canopy (RHc), (A), and temperature of air (Ta) and canopy (Tc), (B) in three row configurations at Clay County, Nebraska, 2006. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped.

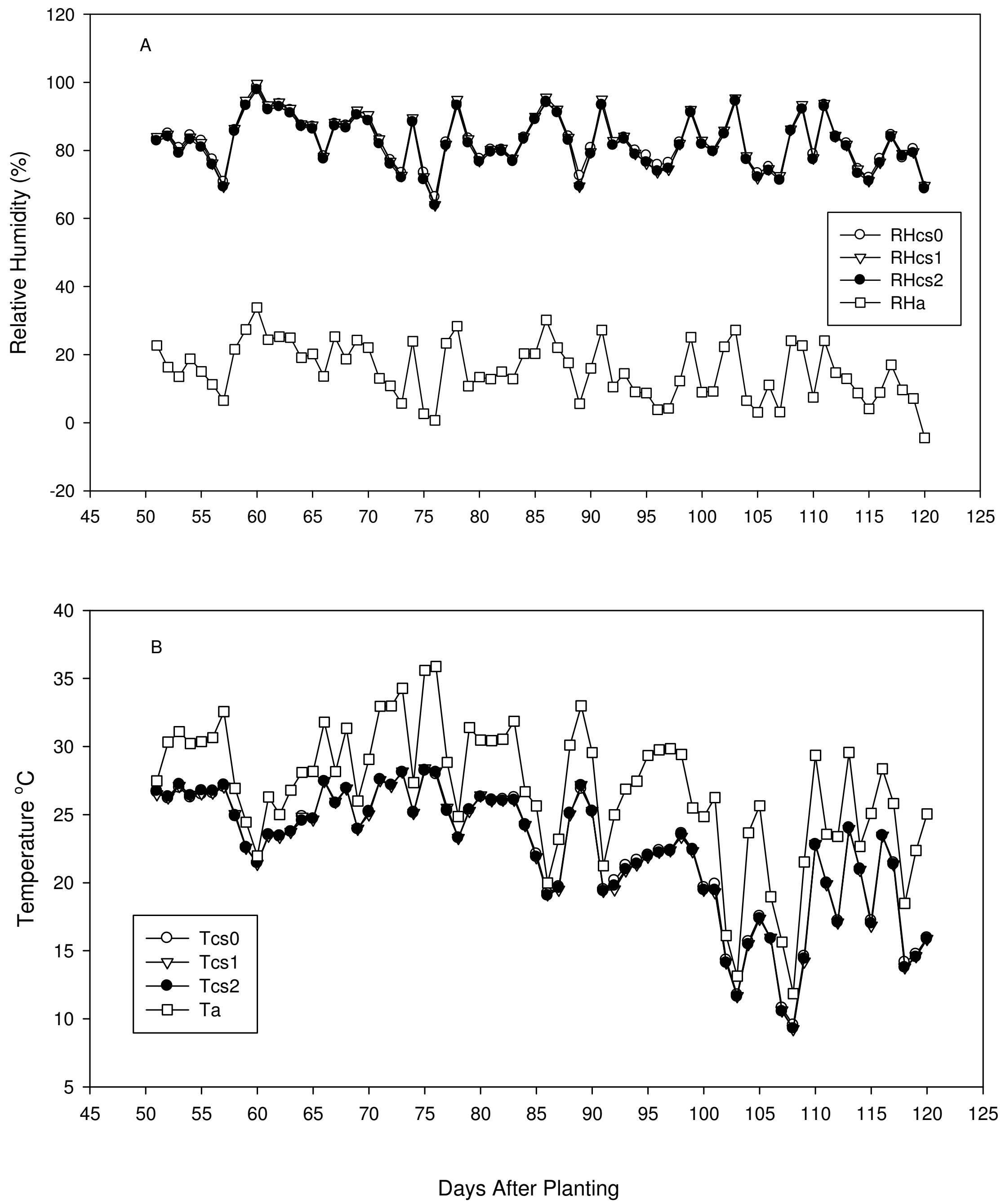

Figure 4.3. Relative humidity of air (RHa) and canopy (RHc) (A), and temperature of air (Ta) and canopy (Tc) (B) in three row configurations at Clay County, Nebraska in 2007. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped.

4.6.4 Biomass, stover and grain yield

Biomass yield at anthesis, and stover yield at physiological maturity were not influenced by the interaction between row configuration and N rates, plant population and N rate or row configuration and plant population. However, interactions between row configuration and N rate significantly influenced grain yield (Tables 4.3 and 4.4).

Row configuration influenced biomass yield at anthesis, as well as stover and grain yield at physiological maturity, in all three years (Fig. 4.4). Nitrogen application increased biomass and grain yield in 2006 and 2007 and stover yield in 2006 (Fig. 4.5). The effects of plant population on biomass yield at anthesis, and stover and grain yield at physiological maturity were not consistent.

Conventional row configuration out-yielded skip-row configurations in biomass, stover and grain all three years (Fig. 4.4). Biomass and grain yield was higher with s1 than with s2 in all years. Sorghum was planted each year when soil water was adequate to ensure good plant establishment. Initial stored soil water and in-season precipitation supported high biomass production with s0 resulting in greater biomass yield and grain yield compared to skip-row planting.

Nitrogen application with skip-row configurations did not affect biomass yield at anthesis in either 2006 or 2007 but resulted in linear increases in biomass yield with s0 with R^2 = 0.86 an 0.79 for 2006 and 2007, respectively (Fig. 4.5). Biomass yield with s0 at anthesis increased linearly with rate of N application and R^2 values of 0.86 for 2006 and 0.79 for 2007. Biomass yield at anthesis with skip-row configurations had a quadratic relationship with R^2 values of 0.93 in 2006 and 0.77 in 2007 for s1 and of 0.81 in 2006 and 0.94 in 2007 for s2 (Figs. 4.5A and B). Stover yield at physiological maturity

followed similar trends as the biomass yield at anthesis. However, it was less responsive to N application in both years with coefficients of determination ranging from 0.63 to 0.99 (Figs. 4.5C and D). The regression equations were not significant for both biomass and stover yield in both 2006 and 2007.

Grain yield response to N application was higher in 2007 than 2006. Increased N rate with s0 configuration resulted in increased grain yield in both years. Wortmann et al. (2007), and Varvel and Wilhelm (2003) reported yield response of grain sorghum to increased N rate. With skip-row configurations, N application resulted in higher grain yield, though increasing N rate above 50 kg N ha^{-1} did not bring any corresponding grain yield increase (Fig. 4.5E and F). This agrees with other research findings that in high yielding environments, yield potential can be significantly reduced when using wider rows due to the inability of the plant canopy to completely cover the ground area and efficiently utilize available net solar radiation (Myers and Foale, 1981; Holland and McNamara, 1982).

However, increasing N rate resulted in a quadratic increase in grain yield with a peak at 150 kg N ha^{-1} with s0. The R^2 values for grain yield ranged from 0.90 to 0.99 for the two years (Fig. 4.5E and F). The relatively low response to N rate observed in 2006 may be attributed to the overall low in-season precipitation (82% of long term average) and the higher climatic deficit (-312 mm) at vegetative and flower stages. According to Eck and Jones (1990), soil water and in-season precipitation are favorable for higher grain yields and increased response to applied N.

Table 4.3. Analysis of variance summary of grain sorghum with three row configurations, two plant populations and four N rates in 2006 at Clay County, Nebraska

		Biomass	Stover	Grain	Grain yield	100 kernel	Panicle	Kernels	HI
		------------Mg ha^{-1}------------			Panicle^{-1} (g)	Weight (g)	m^{-2}	panicle^{-1}	
	DF	---------------------------------------Mean square---							
Row Config (RC)	2	622**	323**	63.11**	12.25ns	0.098**	155**	70562ns	0.0029**
Plant Pop (PP)	1	0.006ns	10.6ns	1.22*	1292**	0.0022ns	62.3**	2543573**	0.0004ns
N rate (N)	3	50.78**	18.2*	10.32**	57.97ns	0.051**	18.2**	81813ns	0.0023ns
RC*PP	2	0.09ns	3.57ns	0.62*	62.57ns	0.0003ns	10.1ns	87421ns	0.0006ns
RC*N	6	11.8ns	5.95ns	1.61**	27.64ns	0.038**	4.02ns	79491ns	0.0006ns
N*PP	3	0.29ns	1.22ns	0.27ns	33.54ns	0.034**	3.24ns	44541ns	0.0004ns
RC*PP*N	6	3.20ns	6.67ns	0.40ns	37.58ns	0.006ns	2.93ns	65307ns	0.0008ns
Residual	46	5.66	5.40	0.20	29.29	0.008	3.64	50666	0.0005

Table 4.4. Analysis of variance summary of grain sorghum with three row configurations, two plant populations and four N rates in 2007 at Clay County, Nebraska.

		Biomass	Stover	Grain	Grain yield	100 kernel	Panicle	Kernels	HI
		------------Mg ha^{-1}------------			$Panicle^{-1}$ (g)	Weight (g)	m^{-2}	$panicle^{-1}$	
	DF	--------------------------------Mean square--------------------------------							
Row Config (RC)	2	467**	901.9**	79.57**	481**	0.330**	177.5**	401549ns	0.037ns
Plant Pop (PP)	1	16.78ns	225.2**	5.12ns	3142**	0.222*	337.6**	3819902**	0.046ns
N rate (N)	3	27.94ns	4.147ns	28.85**	29.91ns	0.067ns	28.03**	81296ns	0.024ns
RC*PP	2	6.97ns	3.653ns	0.40ns	176.7ns	0.035ns	33.73**	217878ns	0.037ns
RC*N	6	17.58ns	5.471ns	8.63**	192.9ns	0.029ns	12.41*	304885ns	0.019ns
N*PP	3	16.20ns	4.743ns	0.83ns	35.60ns	0.011ns	4.30ns	142536ns	0.025ns
RC*PP*N	6	12.59ns	7.566ns	2.46ns	171.4ns	0.033ns	13.43*	178813ns	0.025ns
Residual	46	10.39	9.118	1.62	95	0.050	5.81	152185	0.023

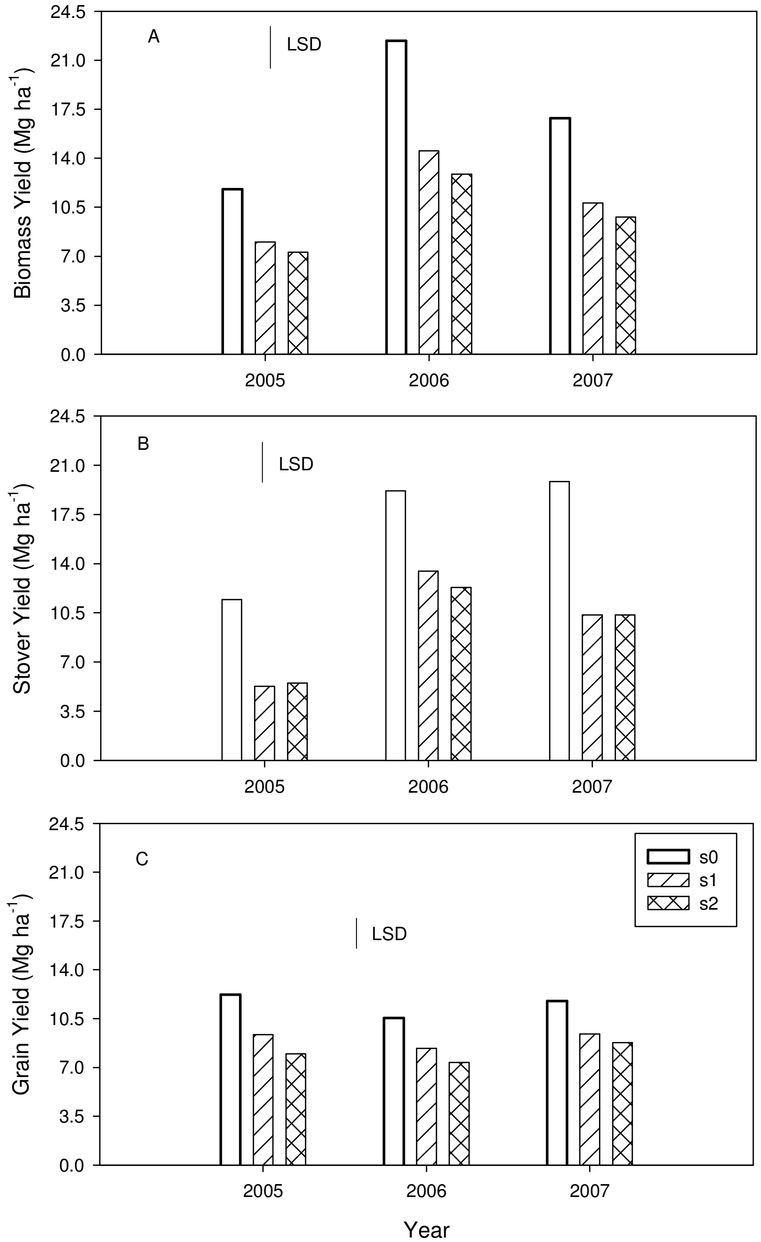

Figure 4.4. Effect of three row configurations on biomass yield at anthesis (A) and stover (B) and grain yield (C) at physiological maturity at Clay County, Nebraska, 2005 to 2007. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped. Y-bars = LSD = 0.05

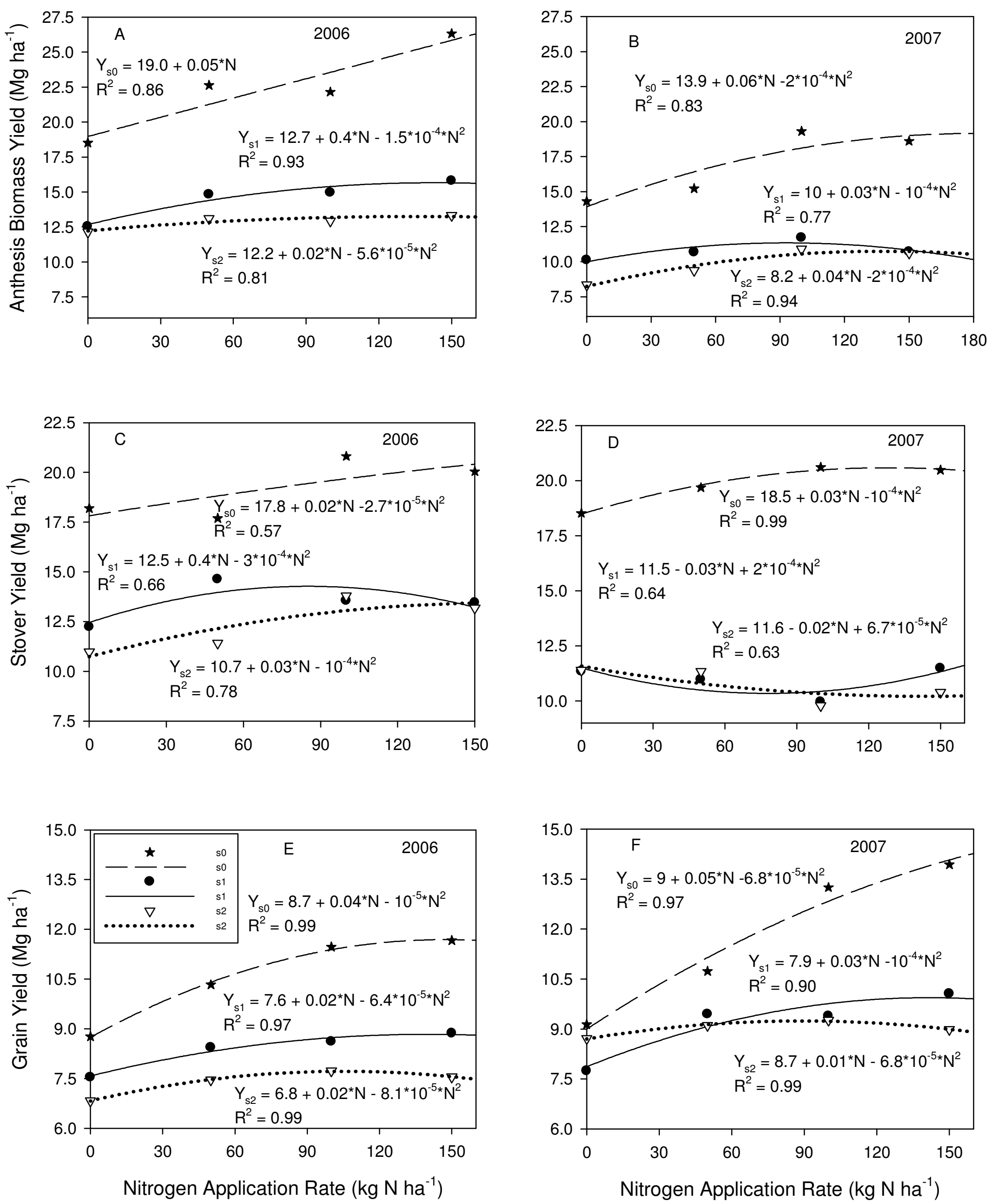

Figure 4.5. The effect of N application and planting configuration on biomass yield at anthesis (A and B), stover (C and D) and grain yield at physiological maturity (E and F) at Clay County, Nebraska in 2006 and 2007. Y = yield, s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped.

4.6.5 Leaf chlorophyll content

Interaction between row configuration and plant population did not result in differences in leaf chlorophyll in 2005, 2006 or 2007. However, significant interaction between row configuration and N rate was observed at reproductive stages in 2006 and 2007 (Tables 4.5 and 4.6). Leaf chlorophyll with s0 was lower than with s1 and s2 at 75 DAP in all three years although grain yield was more with s0. Leaf chlorophyll was similar for s1 and s2 throughout the growing season (Fig. 4.6).

In both 2006 and 2007, treatment with zero N had less chlorophyll than N applied treatments (Fig. 4.7), but leaf chlorophyll was similar for 50, 100 and 150 kg N ha^{-1}. However, the highest N application consistently resulted in the highest leaf chlorophyll throughout the growing season in both years. With s0, increased N rate resulted in increased leaf chlorophyll but the differences between 50, 100 and 150 kg N ha^{-1} became significant only after 75 DAP.

Leaf chlorophyll at 65 DAP had a quadratic relationship with plant N concentration at anthesis and with grain yield at physiological maturity, with respective R^2 values of 0. 97 and 0.98 (Fig. 4.8). The significant relationship suggests that using SPAD-502 at an appropriate growth stage can be useful in detecting N deficiencies in grain sorghum. The relationship between SPAD-502 values and leaf N concentration is consistent with several other studies on maize (*Zea mays*), wheat (*Triticum aestivum*) and potato (*Solanum tuberosum*) leaves (Markwell, et al., 1995; Uddling et al., 2007).

Leaf N and chlorophyll concentrations are closely related and are important physiological parameters of detecting crop N status as most leaf N is contained in chlorophyll (Kramer, 2004). The zero N treatment relied on residual soil N supply which

may be limited as the season progressed and the plant requirement for N increased. This explains the differences in leaf chlorophyll content observed between N and no N treatments after 75 DAP. The skip-row treatments on the other hand had larger inter-row space, likely higher soil temperature and higher mineralization of soil N. This may have resulted in higher leaf chlorophyll N even on zero N treatment with skip-row configuration as indicated by the significant interaction between row configuration and N rate at the reproductive stage in 2006 and 2007 (Tables 4.5 and 4.6).

Carbon dioxide assimilation and biomass production depends on physiological and biochemical processes in plants. Though s0 had lower chlorophyll, the higher leaf area index (Table 4.7) may be responsible for the higher dry matter yield compared to skip-row configurations. Within the s0 configuration, low leaf chlorophyll due to low N application resulted in low biomass production in both years. Zhao et al. (2005) reported that N deficiency in grain sorghum caused reduced leaf area, reduced chlorophyll and photosynthetic rate resulting in lower biomass production. They explained that the reduction in biomass under N-stress was due to decreased stomatal conductance as a result of lower intercellular CO_2 concentration. However, according to Heitholt et al. (1991), N deficiency in crops reduce ribulose biphosphate carboxylase/oxygenase (Rubisco) activity. Maranville and Madhavav (2002) reported that phosphoenolpyruvate carboxylase (Pepcase) and Rubisco activity in sorghum leaf was reduced by N deficiency.

Table 4.5. Analysis of variance summary of grain sorghum leaf chlorophyll with three row configurations, two plant populations and four N rates in 2006 at Clay County, Nebraska.

		55	62	77	110
	DF	---------------------------Mean square------------------------------			
Row Config. (RC)	2	1925.5ns	5273.8*	11515**	152508**
Plant Pop (PP)	1	4777.7*	17313**	726.6ns	9269.9**
N rate (N)	3	17488**	17276**	20828**	100621**
RC*PP	2	850.7ns	1260.7ns	1160.4ns	186.3ns
RC*N	6	13.48.3ns	1076.5ns	7136**	17843**
N*PP	3	2896ns	742.2ns	410.9ns	2424.3ns
RC*PP*N	6	1670.4ns	974.9ns	1547.8ns	2367.6ns
Residual	46	1163.7	1283	1978.7	1322.9

Table 4.6. Analysis of variance summary of grain sorghum leaf chlorophyll with three row configurations, two plant populations and four N rates in 2007 at Clay County, Nebraska.

		53	63	77	107
	DF	------------------------------Mean Square-------------------------			
Row Config. (RC)	2	17587**	4843.3ns	88361**	99455**
Plant Pop (PP)	1	35803**	57292**	33461**	22601**
N rate (N)	3	83470**	89039**	108488**	76860**
RC*PP	2	401.4ns	168.5ns	40.87ns	1096.8ns
RC*N	6	5169.7**	3116.8ns	3913.3ns	12722**
N*PP	3	617.7ns	2565.6ns	2334.7ns	2288ns
RC*PP*N	6	1725ns	4160.7ns	2951.5ns	5527.3ns
Residual	46	1383.7	2579.9	2631.5	2703.1

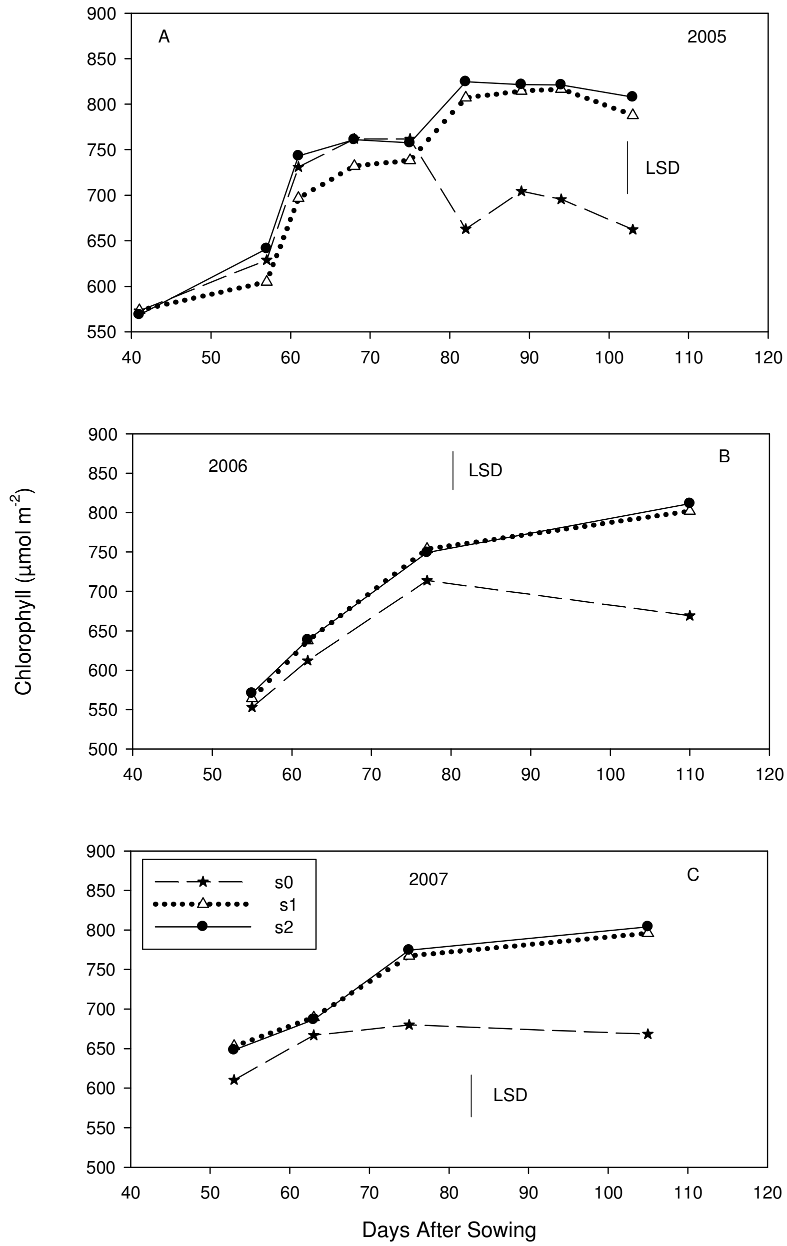

Figure 4.6. Effect of three row configurations averaged over N on leaf chlorophyll content during the growing season at Clay County, Nebraska, 2005 to 2007. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped. Y-bars = LSD = 0.05.

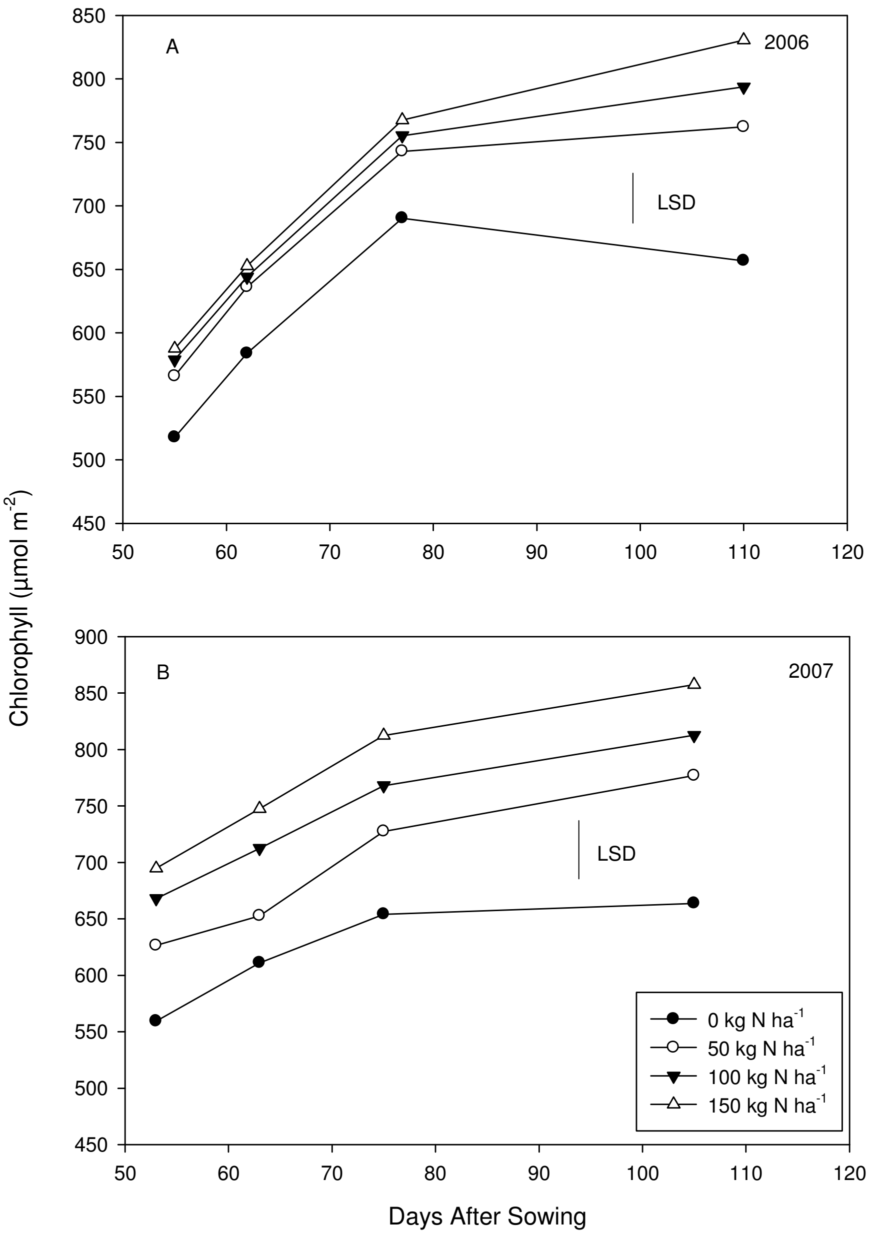

Figure 4.7. Effect of four nitrogen rates averaged over row configurations on leaf chlorophyll content during the growing season at Clay County, Nebraska in 2006 and 2007**.** Y-bars = 0.05

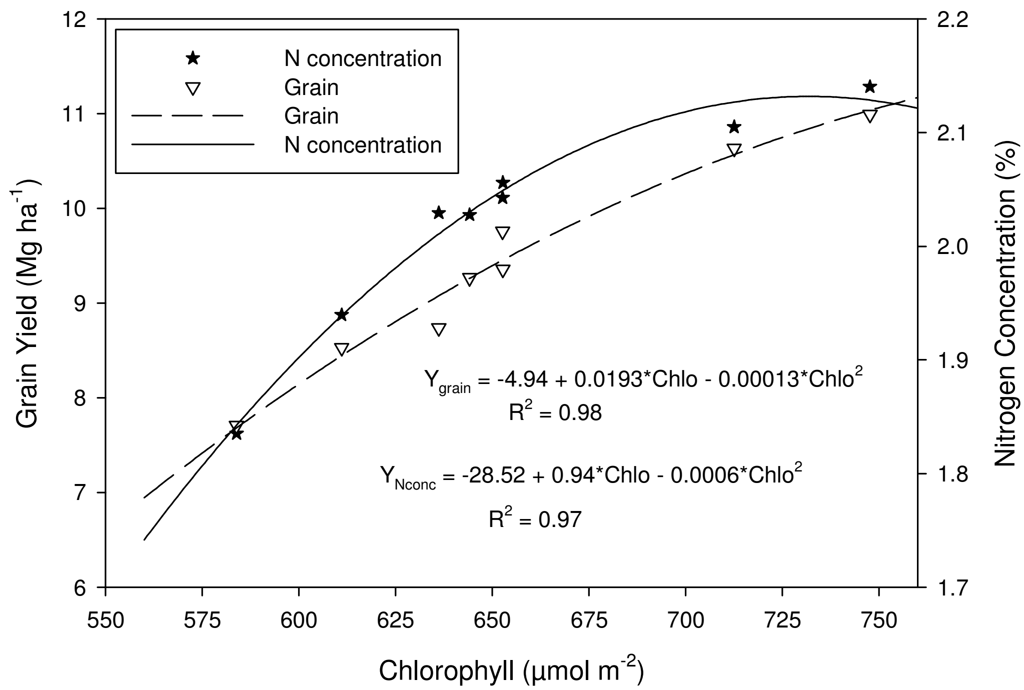

Figure 4.8. Relationship between leaf chlorophyll and N concentration at 65 DAP and grain yield at harvest over a 2-year period at Clay County, Nebraska.

Table 4.7. Effect of row configuration on leaf area index of grain sorghum at 65 and 75 days after planting in 2006 and 2007 at Clay County, Nebraska.

	2006		2007	
Row Configuration	65 DAP	75 DAP	65 DAP	75 DAP
	----------------LAI----------------			
s0	4.94	5.04	4.60	4.71
s1	2.94	3.21	3.36	3.38
s2	2.79	3.09	2.94	3.20
LSD	0.30	0.25	0.32	0.38

4.6.6 Nitrogen concentration, uptake and nitrogen use efficiency

Nitrogen concentration in both anthesis biomass and grain was not influenced by interactions of row configuration, plant population and N rate in 2006 and 2007 (Tables 4.8 and 4.9). Row configuration x N rate interaction significantly influenced biomass N uptake in 2006 and grain N uptake in 2007. Row configuration x plant population interaction significantly influenced partial factor productivity NUE (PFP_N) in 2006, agronomic NUE (AE_N) in 2006 and 2007, and recovery NUE (RE_N) in 2006 and 2007.

Increased N rate resulted in increased grain N concentration and uptake in 2007 but not in 2006 (Fig. 4.9). Kamoshita et al. (1998) reported that increased N application resulted in increased grain N concentration in grain sorghum. While increasing N resulted in increasing in N uptake by grain with s0, no apparent increases in N uptake was observed with s2 (Fig. 4.9C). As N rate increased, the amount of N relocated from

biomass to grain increased in both 2006 and 2007. The amount of N relocated from biomass to grain in 2006 ranged between 29 and 35% compared to 46 and 51% N relocated to the grain in 2007.

Averaged over N rates, PFP_N and AE_N indices with s0 had higher NUE than with s1 and s2 in 2006 and 2007 (Fig. 4.10). Application of N at 50 kg ha^{-1} gave significantly higher NUE than 100 and 150 kg N ha^{-1} in both years using PFP_N and AE_N indices. With each row configuration, raising the N rate above 50 kg ha^{-1} resulted in the reduction in PFP_N and AE_N in 2006 and 2007. According to Dobermann (2005), PFP_N is a more appropriate index to farmers because it integrates the use efficiency of both indigenous and applied N resources. Other studies with grain sorghum found similar reductions in NUE with increased N application (Wortmann et al., 2007; Buah et al., 1998).

Lower NUE indices obtained with skip-row are likely related to the lack of full canopy cover with skip-row configurations, limiting the ability of the crop to fully utilize solar energy for photosynthetic processes. Since water stress was not observed in this study, differences in N use efficiency can be attributed to under-utilization of N and other resources such as solar radiation. According to Cechin (2004), water stress in sorghum will reduce N concentration, stomatal conductance, transpiration and photosynthetic rate compared with well watered plants. Other factors that can be responsible for low NUE in sorghum are cultivars (Gardner et al., 1994), management system (Sow et al., 1998) and soil available water (Stewart and Steiner, 1990).

Table 4.8. Analysis of variance summary for grain sorghum with three row configurations, two plant populations and four N rates in 2006 at Clay County, Nebraska.

		Biomass	Grain	Biomass	Grain	PFP_N	AE_N	RE_N
	DF	---- N Concentration (%)-----		-----N Uptake (kg ha^{-1})-----		-------------------kg kg^{-1}---------------------		
Row Config (RC)	2	0.046ns	0.594**	226060**	357.1ns	7848**	1439**	0.073ns
Plant Pop (PP)	1	0.055ns	0.171**	865.9ns	841.7ns	304.5ns	71.8ns	0.011ns
N rate (N)	3	0.275**	0.325**	30107**	4325**	6086*	414.9*	0.007ns
RC x PP	2	0.034ns	0.016ns	700.9ns	101.4ns	1672*	567.3**	0.392**
RC x N	6	0.052ns	0.039ns	12355**	687.3ns	363.9ns	16.4ns	0.199*
N x PP	3	0.026ns	0.034ns	2409.1ns	31.8ns	200.2ns	127.8ns	0.012ns
RC x PP x N	6	0.073ns	0.029ns	4865.3ns	544.4ns	70.4ns	126.1ns	0.142ns
Residual	46	0.043	0.030	396.1	290.8	76.8	95.8	0.071

* Significant at 5% or less, ** Significant at 1% or less, ns Not significant

Table 4.9. Analysis of variance summary for grain sorghum with three row configurations, two plant populations and four N rates in 2007 at Clay County, Nebraska.

	DF	Biomass	Grain	Biomass	Grain	PFP_N	AE_N	RE_N
		N Concentration (%)		---N Uptake (kg ha^{-1})----		---------------------kg kg^{-1}------------------------		
Row Config. (RC)	2	0.474**	1.135**	151645**	740.9ns	8651.4**	3966**	0.180ns
Plant Pop (PP)	1	0.756**	0.072*	3801.4ns	5680**	757.2*	397.7ns	0.333ns
N rate (N)	3	0.059ns	0.72*	16022ns	4967**	95394**	406.3ns	0.138ns
RC*PP	2	0.126ns	0.008ns	10932ns	265.1ns	119.3ns	1921*	0.763*
RC*N	6	0.166ns	0.005ns	17671ns	1576.4*	110.7ns	348.6ns	0.174ns
N*PP	3	0.056ns	0.001ns	14075ns	59.4ns	5.1ns	6.0ns	0.009ns
RC*PP*N	6	0.160ns	0.021ns	23083ns	1216.4ns	377.5ns	3551.1ns	0.199ns
Residual	46	0.080	0.015ns	9576	569.6	190.7	500.5	0.205

* Significant at 5% or less, ** Significant at 1% or less, ns Not significant

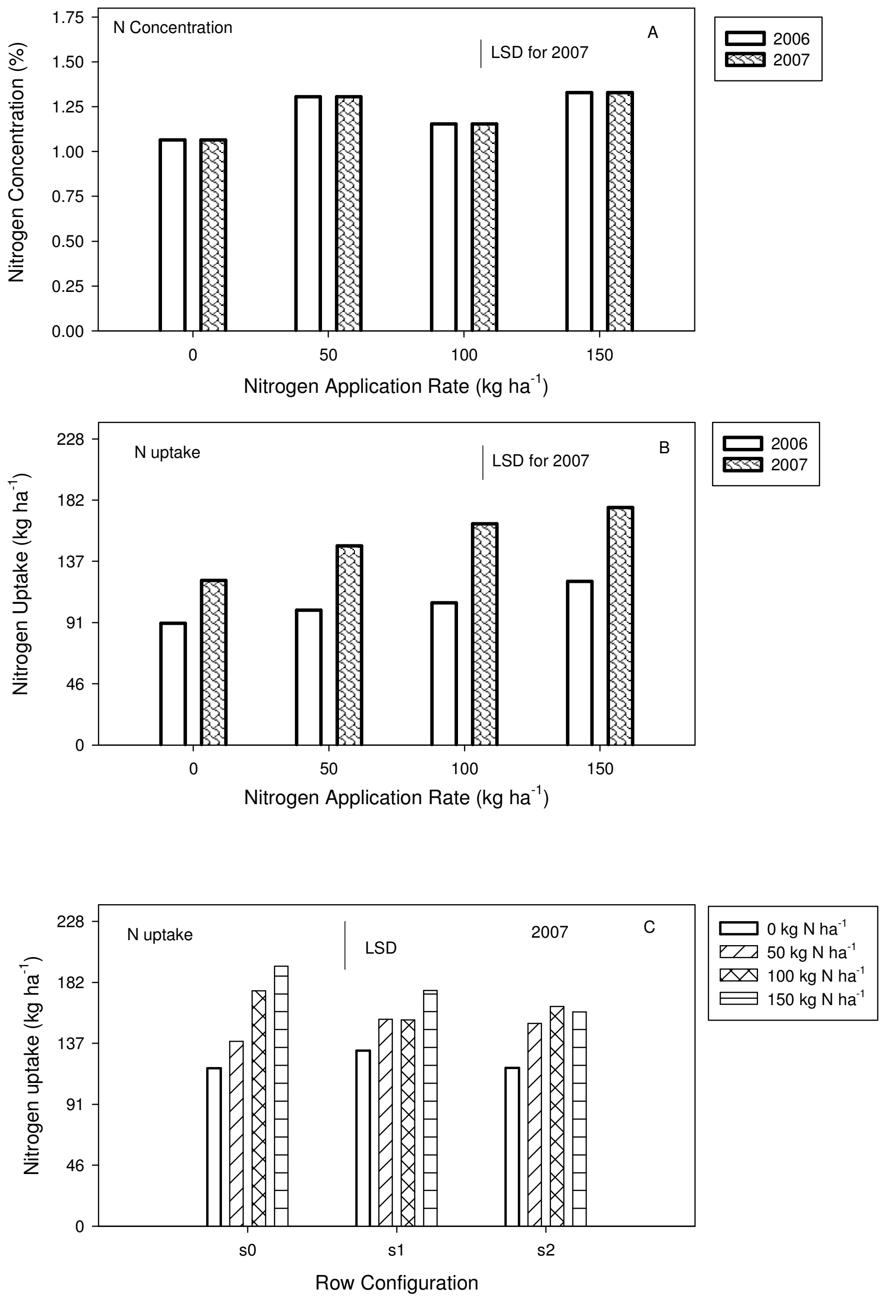

Figure 4.9. Effect of N application rate on grain N concentration (A), uptake (B) averaged over three row configuration in 2006 (plain bar) and 2007 (shaded bar), and (C) interaction between N rate and row configuration in 2007 at Clay County, Nebraska. Y-bars = LSD 0.05 within site-years.

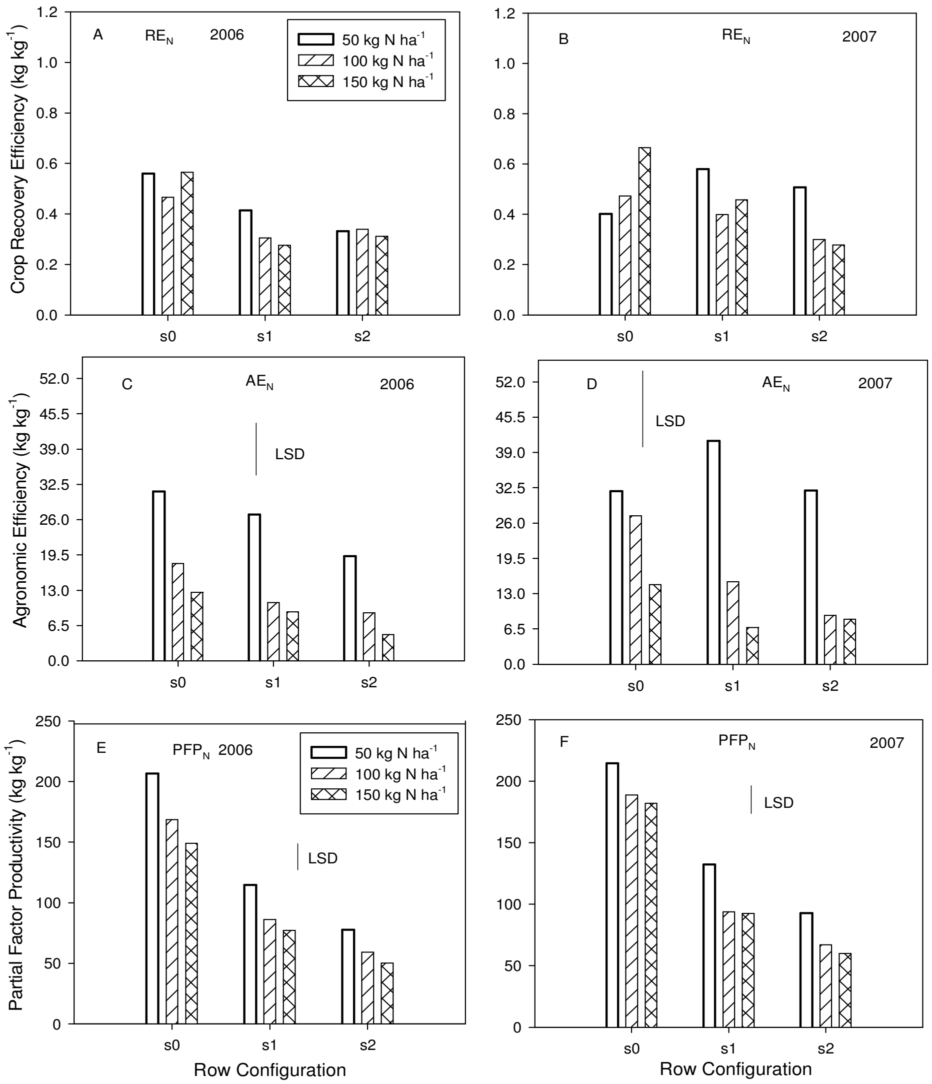

Figure 4.10. Effect of N application rate and row configurations on crop recovery N efficiency (RE_N) in 2006 and 2007 (A and B), agronomic N efficiency (AE_N) in 2006 and 2007 (C and D), and partial factor productivity of N (PFP_N) in 2006 and 2007 (C and D) at Clay County, Nebraska. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped. Y-bars = LSD = 0.05 within site-year

4.7 Conclusions

Rainfall is normally adequate in south-central Nebraska such that s0 yields are likely to be higher than s1 and s2 yields. Canopy temperature during the season did not indicate soil water deficit stress with any row configuration. Grain sorghum yield, N concentration and N uptake were influenced by N rates. Grain yield response to N rate for each row configuration was quadratic in 2006 and 2007 with very high coefficients of determination. With each row configuration, the addition of 50 kg N ha^{-1} increased NUE but raising the rate to 100 or 150 kg N ha^{-1} resulted in significant reduction in NUE. Addition of 150 kg N ha^{-1} with s0 and 100 kg N ha^{-1} with skip-row planting gave the highest grain yield to N application in both years.

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CHAPTER FIVE

SPECTRAL REFLECTANCE MEASUREMENTS OF LEAF AND CANOPY FOR NON-DESTRUCTIVE ASSESSMENT OF N STATUS IN GRAIN SORGHUM.

5.1 Abstract

Nitrogen is major determinant and the most readily managed variable for grain yield in crops. A quick and non-destructive detection of crop N status using remote sensing techniques could provide increased N use efficiency. Remote sensing and analytical techniques were used to evaluate N stress on grain sorghum in a greenhouse and in the field in 2006 at the South Central Agricultural Laboratory, University of Nebraska. The objectives of the study were to evaluate the relationship between spectral reflectance and N status in leaf and canopy of grain sorghum, and to develop indices sensitive to leaf and canopy N content. N stress decreased both chlorophyll meter reading and leaf N content. Water and N stresses resulted in an increase of leaf and canopy reflectance. Spad-502 values were significantly increased by both water and N stress. A model calibrated in the greenhouse using a reciprocal index in the green and NIR range, $R[_{(549\text{-}569)}]^{-1}$ and $R[_{(549\text{-}569)}]^{-1}$ - $R[_{(750)}]^{-1}$ and in the red edge and NIR, $R[_{(710\text{-}718)}]^{-1}$ and $R[_{(710\text{-}718)}]^{-1}$ - $R[_{(750)}]^{-1}$ predicted leaf chlorophyll content with RMSE ranging between 52 and 56 mg m^{-2}. The model calibrated for canopy chlorophyll estimation had a quadratic relationship with canopy chlorophyll, with R^2 ranging between 0.69 and 0.78.

5.2 Introduction

Sorghum, (*Sorghum bicolor* (L) Moench), is the fifth most important cereal after rice, wheat, maize, and barley. Sorghum is a major food grain for over 750 million people in the semi-arid tropics of Africa, Asia, and Latin America and is an important commercial and export crop in the United States of America, Australia, and Argentina (Carter et al., 1989). Moreover, improved varieties respond to N and water stresses as any of the other cereals (Chapter 4, Maman et al., 2003; Zhao et al., 2005). It is more tolerant of drought and nutrient stresses than some other cereals and often well-adapted to semi-arid conditions. Nitrogen is one of the most important nutrients required for optimum grain sorghum yield but lack of available water reduces N uptake and decreases yield response to N (Ferguson, 2000). The effect of adequate water and N supply on grain yield is greater than the yield increase from adequate supply of either factor alone.

Determining N status by remote sensing is one tool to improve N management and yield predictions in many crops. Several studies have reported the use of remote sensing to quantify N stress in many plant species (Graef and Claupein, 2003; Osborne et al., 2002; Schlemmer et al., 2005; Gitelson et al., 2005). However, there are few studies on the use of remote sensing to monitor and evaluate N stress in grain sorghum either at canopy or leaf levels (Mandal et al., 2007; Zhao et al., 2005).

When radiation corresponding to the wavelengths of pigment absorption bands is incident upon green vegetation, the reflectance is reduced to a varying extent, depending on the tissue pigment content (Thomas et al., 1971; Tucker, 1980). Absorption by water and pigments determine to a large extent the reflectance spectrum of a leaf (Gates et al., 1965; Knipling, 1970; Woolley, 1971; Tucker and Garratt, 1977). Chlorophyll and

accessory pigments absorb strongly between 400 and 700 nm. Reflectance indices for the estimation of plant N status have been developed, but only a few of these indices were developed and tested on grain sorghum (Mandal et al., 2007; Zhao et al., 2005). Also few studies considered the combined effect of water and N availability and its effects on leaf or canopy reflectance. Richardson et al. (2002) derived two indices for chlorophyll estimation but caution that differences in leaf structure may necessitate species-specific calibration equations.

5.3 Hypothesis and objectives

Leaf and canopy reflectance of grain sorghum can be used as an indicator of N and water stress and these stresses can be evaluated with leaf or canopy reflectance.

The study evaluated relationships between leaf and canopy spectral reflectance and water and N stresses of grain sorghum. Specific objectives of the study were:

i. Determine reflectance patterns of sorghum leaf and canopy exposed to N and water stress.
ii. Identify spectral bands in which leaf and canopy reflectance were most affected by N content.
iii. Evaluate spectral indices for the detection of N stresses in grain sorghum at both canopy and leaf level and compare these with published indices.

5.4 Materials and Methods

The effect of water and nitrogen stresses on spectral reflectance of grain sorghum was addressed in a greenhouse study conducted from February to April 2006 and in a field study conducted in 2006. In the greenhouse study, 45 pots with capacity of 9.45 L were filled with equal volumes of soil mixed with sand. Five rates of inorganic nitrogen (N): 0, 34, 68, 100 and 135 kg N ha^{-1} as urea were applied per pot. Fifty percent of N, 45 kg P ha^{-1} and 20 kg K ha^{-1} were applied before planting. The remaining 50% of urea was applied equally at 28 days after emergence (DAE) and 42 DAE to minimize leaching of nitrate-N from the pots. A medium maturity sorghum hybrid, Dekalb 42-20, was planted and thinned to three plants per pot after emergence. A completely randomized design (CRD) with three replications was used. Twelve hour (7am – 7pm) 400 watt incandescent light was used and temperature in the room was kept at 29/18^{o}C for day and night temperature, respectively.

Three levels of soil matric potential were imposed beginning 32 days after emergence (DAE): adequate soil water (NS) (>20 kPa); medium water stress (MS) (40<kPa<80), and water stress (S) (>100 kPa). Soil matric potential was recorded with Watermark sensors (Irrometer Co., Riverside, CA, USA) installed in each pot. Each Watermark sensor was connected to a data logger and soil water matric potential was logged hourly. At 75 DAE, Minolta SPAD-502 chlorophyll meter (Minolta Co., Osaka, Japan) readings were taken from the middle section along the length and midway between the margin and the midrib of the most recently fully expanded leaf. Six measurements were taken per leaf and averaged to a single value. The three leaves used for SPAD-502 reading were removed, kept in a polyethylene bag under ice and sent to

the laboratory (Daughtry and Biehl, 1985). Plants in each pot were harvested, weighed immediately, and then dried at 70^{o} C for 72 hrs to determine dry weight.

5.4.1 Reflectance measurement, relative water content and chlorophyll extraction

Spectral reflectance of the three previously used leaves for Spad-502 measurement was measured with an ASD Fieldspec FR spectroradiometer (Analytical Spectral Device, Boulder, CO) connected to a Li-COR integrating sphere (LI-COR Inc., Lincoln, NE). A $BaSO_4$ reference was used to calibrate all reflectance measurements. Six scans were taken per leaf. Each spectral scan measured reflectance from 350 to 2500 nm at 1-nm increments. The spectral data was converted to reflectance and the data above 2200 nm was discarded due to high noise to signal ratio. Relative water content (RWC) and total chlorophyll content of the incised leaves were determined. Five 1-cm disks were taken from the each leaf. Ten disks were selected randomly and weighed immediately providing a measure of fresh weight (L_f). The leaf disks were soaked in deionized water for 24 hours and then weighed again to obtain the turgid weight (L_t). Finally, the leaf disks were dried at 85^{o}C and weighed to obtain a dry mass (L_d). The RWC was calculated (Salisbury and Ross, 1992) as:

$RWC = (L_f - L_d)/(L_t - L_d)$.

The remaining set of five leaf disks were used to determined chlorophyll content using the dimethyl sulphoxide (DMSO) chlorophyll extraction technique (Hiscox and Israelstam, 1979; Barnes et al., 1992; Richardson et al., 2002). Ten milliliters of DMSO and leaf disks were placed in a 65^{o}C water bath for 30 minutes. The DMSO extract was

read on a DU 800 spectrophotometer to acquire absorption (A_λ) measurements at 500 to 750 nm wavelength, which was used to calculate chlorophyll concentration (Chl_{conc}). Equations for Chl *a* and Chl *b* as provided by Wellburn (1994):

$$Chl\ a = 12.19A_{665} - 3.45A_{649};\ (\mu g\ ml^{-1})$$

$$Chl\ b = 21.99A_{649} - 5.32A_{665};\ (\mu g\ ml^{-1})$$

$$Total\ Chl_{conc} = Chl\ a + Chl\ b;\ (\mu g\ ml^{-1})$$

Chlorophyll content was derived as a function of chlorophyll concentration, the volume of DMSO ($DMSO_{vol}$) used in the extraction, and the leaf disk area sampled:

$$Chlorophyll\ (Chl)\ content = (total\ Chl_{conc} * DMSO_{vol})/LDA;\ (mg\ m^{-2})$$

5.4.2 Field study

The study was conducted in the summer of 2006 at the University of Nebraska Institute of Agriculture and Natural Resources, South Central Agricultural Laboratory (SCAL) near Clay Center, Nebraska (lat. 40^{o}34'N; long; 98^{o}08W; 543.3 m elevation). For detailed experimental setup and treatments see chapter 2.

5.4.3 Canopy reflectance measurement in the field

At 75 DAP, an Analytical Spectral Devices (ASD) FieldSpec Pro FR spectrometer connected to a computer and mounted on a high-clearance tractor was used to measure in-situ upper canopy reflectance. The spectral profiles were collected under sunny and cloudless conditions between 10:00 and 14:00 h. Three spectral measurements per plot were taken from nadir about 1.5 m over the canopy. A white reference Spectralon calibration panel was used between every three measurements to account for the

changing atmospheric conditions and irradiance of the sun, removing the effects of changing solar illumination. The spectral reflectance of the vegetation was calculated as a fraction of the approximately 100% reflectance of the white panel. Leaf chlorophyll concentration was determined as described in the greenhouse study. Total leaf Chl content was converted to canopy chlorophyll (CChl) content (Gitelson et al., 2005):

CChl = Chl content*green LAI.

Using the concept proposed by Gitelson et al. (2003), four indices were calibrated $R[_{(green)}]^{-1}$, $R[_{(green)}]^{-1} - R[_{(NIR)}]^{-1}$, $R[_{(RE)}]^{-1}$, $R[_{(RE)}]^{-1} - R[_{(NIR)}]^{-1}$, where $R[_{(\lambda)}]^{-1}$ is the reciprocal reflectance of green, red edge (RE) and near infrared (NIR) and compared with indices listed below:

Simple ratio index (SR) = R_{NIR}/R_{RED} Rouse et al. (1974)

NDVI = $(R_{NIR} - R_{RED})/(R_{NIR} + R_{RED})$ Rouse et al. (1974)

GNDVI = $(R_{NIR} - R_{GREEN})/(R_{NIR}+R_{GREEN})$ (Gitelson et at. (1996)

5.5 Data analysis:

All data were analyzed by analysis of variance mixed linear model procedure (Proc Mixed, SAS Institute, 2007, Cary, NC, USA). Where the F test was significant at $P \leq 0.05$, the least significant difference (LSD 0.05) was calculated and used to separate treatment means. Regression analysis was performed to establish relationships of reflectance with SPAD-502 values, chlorophyll content and biomass yield. Greenhouse data was divided into two groups. One set was used to calibrate the model and the second data set was used for model validation.

5.6 Results and Discussion

5.6.1 Relationship of Spad-502 values with chlorophyll content and dry matter yield in a greenhouse study

The interaction of N rate and water application significantly influenced dry matter yield, chlorophyll content, Spad-502 values, and the reflectance of 1455-1465 nm and mean of 1760-1770 nm (Table 5.1). Several studies have reported significant water and N interactions on growth and development and biophysical characteristics (Schepers et al., 1996; Martinez and Guiamet, 2004; Zhao et al., 2005).

Soil water matric potential was lower with no stress (NS) than with medium (MS) and water stress (S) treatments after 40 DAP. However, differences in water potential between MS and S condition were not apparent until 65 to 75DAP (Fig. 5.1). N rate significantly influenced all parameters measured except soil water matric potential (Table 5.1). Water stress resulted in significant differences in all parameters measured except leaf total chlorophyll content.

At each water level, the best fit function of the relationship between N rate and biomass yield was power with R^2 values of 0.99 with NS and 0.98 with MS and S (Fig. 5.2A). Water stressed plants responded less to increased N rate and the response to N leveled off after 60 kg N ha^{-1}. Medium stress and NS plants reached a plateau between 90 and 120 kg N ha^{-1}. At any N rate, stressed plants had lower yield per kg N applied compared to MS and NS treatment.

With an adequate water supply, Spad-502 values and chlorophyll content had a positive linear relationship with N rate, while the best fit function was power for MS and S conditions with R^2 values of 0.92 with MS and 0.98 with S (Fig. 5.2B). With NS, the

relationship between leaf chlorophyll and N rate was linear with R^2 value of 0.97. While with MS and S, quadratic functions with R^2 values of 0.84 and 0.98 with MS and S described the relationship between leaf chlorophyll and N rate (Fig. 5.2C).

There was a quadratic relationship between Spad-502 and chlorophyll content with chlorophyll increasing with increase in Spad-502 and a coefficient of determination of 0.88 (Fig. 5.3A). Significant relationships between Spad-502 values and chlorophyll content have been reported in several studies (Markwell et al., 1995; Schepers et al., 1996; Martinez and Guiamet, 2004). Since much of leaf N is incorporated in chlorophyll, chlorophyll in leaves has been used to assess N status of crops (Filella et al., 1995, Moran et al., 2000). Chlorophyll meters have been used to detect N stress in corn (Zea mays L.) leaves (Schepers et al., 1992; Wood et al., 1992; Blackmer et al., 1994).

In this study, water stress decreased Spad-502 values and reduced the relative water content of the leaf (Fig. 5.4). Relative water content (cell turgor) in plants growing under field conditions has been found to vary significantly during the day (Piekielel et al., 1995; Hirasawa and Hsiao, 1999; Yang et al., 2001). Martinez and Guiamet (2004) observed that Spad-502 values increased when a maize leaf was dehydrated and reduced when the same leaf was re-hydrated in a laboratory. However, Schepers et al. (1996) and Schlemmer et al. (2005) reported that water stress in maize leaves reduced Spad-502 values. Water stress in plants reduces RWC and cell turgor and this increase transmittance of the near infrared energy through the leaf tissue. The intercellular air spaces in the leaf tissue are influenced by cell turgor which is directly influenced by plant water status (Gausman et al., 1974). Spad-502 output is a function of leaf transmittance in

the red and NIR (650 and 940 nm) wavelength and is affected by changes in the intercellular air spaces of the leaf.

The increase in dry matter yield relative to Spad-502 and chlorophyll content was quadratic with R^2 of 0.86 and 0.85, respectively (Figs. 5.3B and C). Although SPAD-502 measurements are rapid and easy, the measurement represents a very small portion of a leaf. Water stress, leaf age and time of the day influence Spad-502 readings (Schepers et al., 1996; Martinez and Guiamet, 2004; Schlemmer et al., 2005). The use of Spad-502 in predicting leaf N status in grain sorghum and other plants must be guided by water status of the crop since Spad-502 tends to under-estimate leaf N status under water stress.

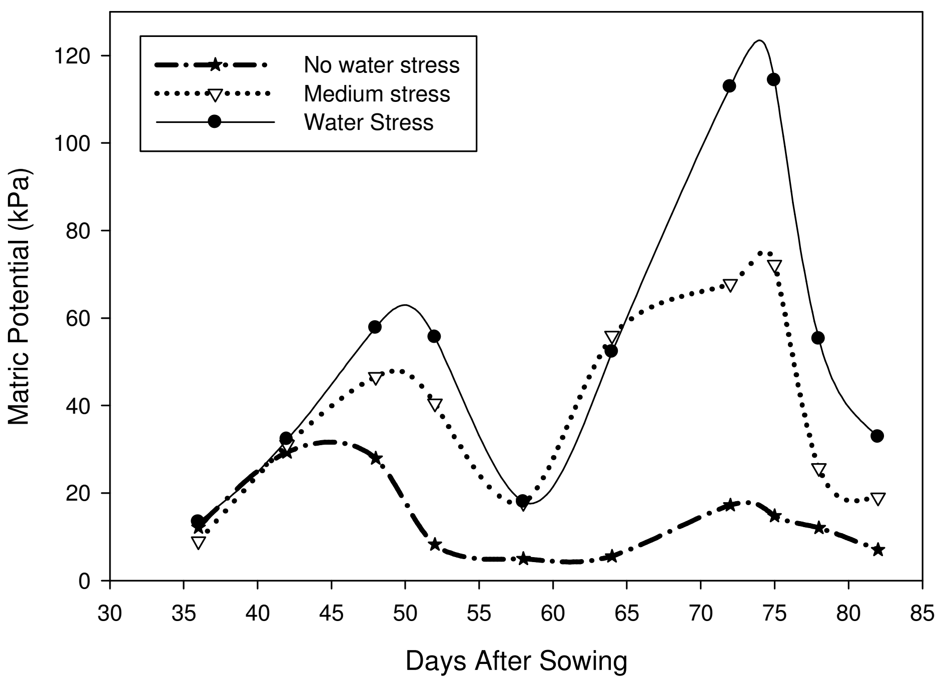

Figure 5.1. Mean Watermark sensor readings of soil water matric potential in pots over time for grain sorghum in a greenhouse.

Table 5.1. ANOVA summary for a greenhouse study with N rates of 0, 34, 68, 100 and 135 kg N ha^{-1} under no water stress (NS), medium water stress (MS) and water stress (S) at 75DAP.

Source	DF	DMY	Chl	SPAD	RWC	WMS	R_{550}	R_{703}	$R_{549-560}$	$R_{710-718}$	$R_{1450-1470}$	$R_{1760-1770}$
Units		g	Mg m^{-2}		%	kPa	--%-------------------------------					
		----------Mean Square----------										
N rate (N)	4	623**	105063**	363**	0.205**	1588ns	68.1**	65.5**	68.0 **	76.9**	12.8**	8.10**
Water level(W)	2	132**	809.5ns	7.2**	0.084**	41043**	19.8**	16.8**	20.1**	19.5**	14.8**	10.9**
N*W	8	21.3**	3411**	11.1**	0.014ns	408ns	2.81ns	2.54ns	2.78ns	4.61ns	4.95**	3.74**
Residual	28	0.83	377	0.92	0.002	644.7	2.43	2.35	2.45	2.57	1.74	0.81

†Dry matter yield (DMY), total leaf chlorophyll (Chl), Spad-502 values (SPAD), Relative water content (RWC), Plant water content (PWC), Watermark sensor (WMS)

‡Reflectance, R at 550, 703, average of 550 to560, 710 to 717, 1450 to 1470 and 1760 to 1770 nm wavelength.

* Significant at 5%, ** Significant at 1% or less, ns Not Significant.

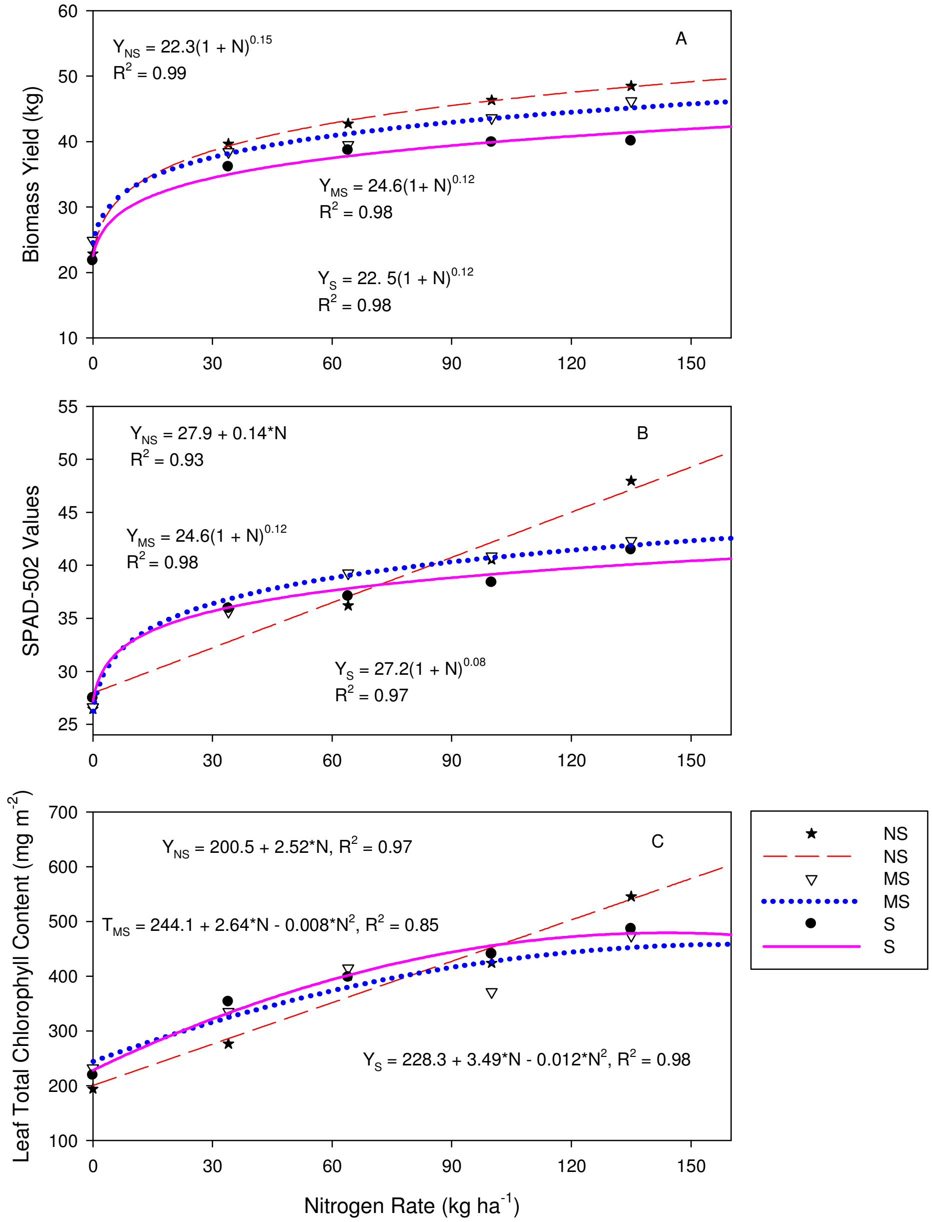

Figure 5.2. Effect of five N rates and three water availability levels on grain sorghum biomass yield (A), SPAD-502 values (B) and total chlorophyll concentration (C) at 75 days after sowing in a greenhouse. NS, No water stress, MS, medium water stress, S, water stress.

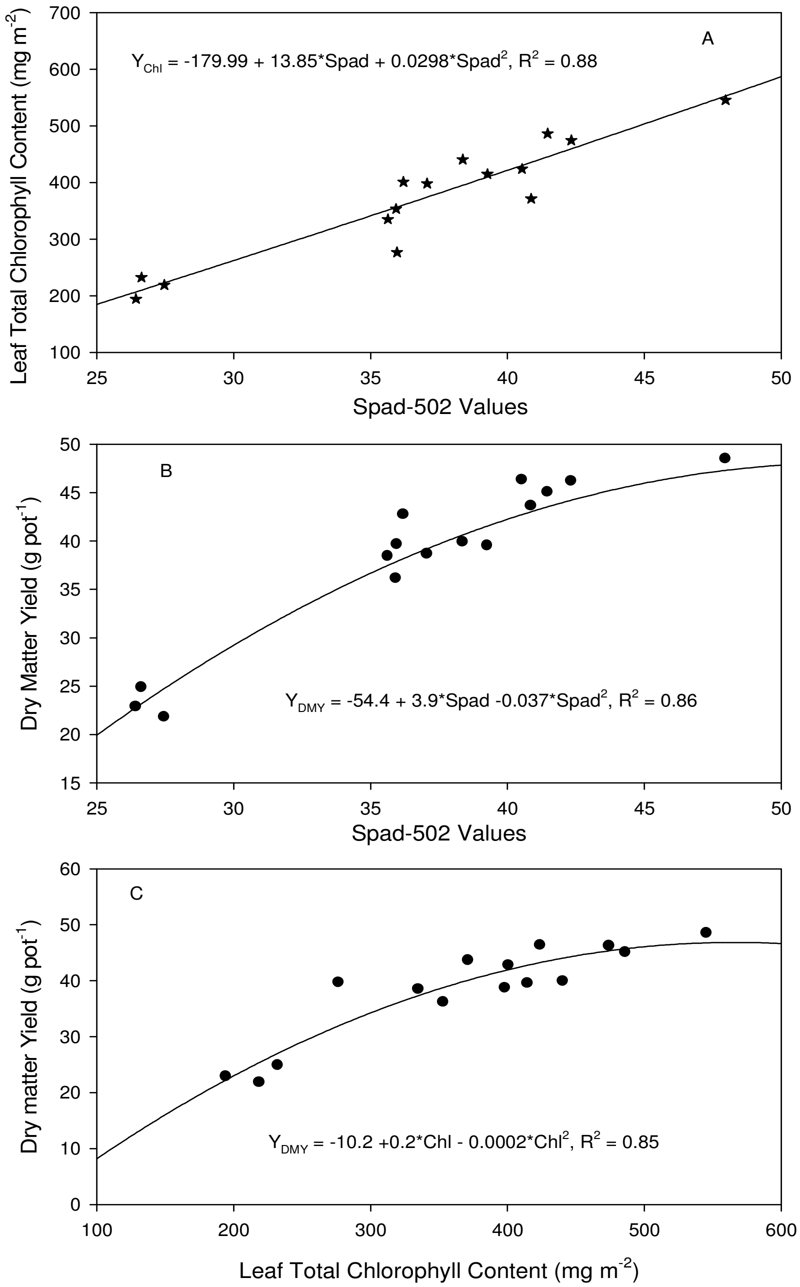

Figure 5.3. Best fit relationships of Spad-502 values with grain sorghum leaf total chlorophyll content (Chl) (A), Spad-502 with dry matter yield (B), and of Chl with dry matter yield (C) across five N rates and three water levels at 75 days after sowing in a greenhouse.

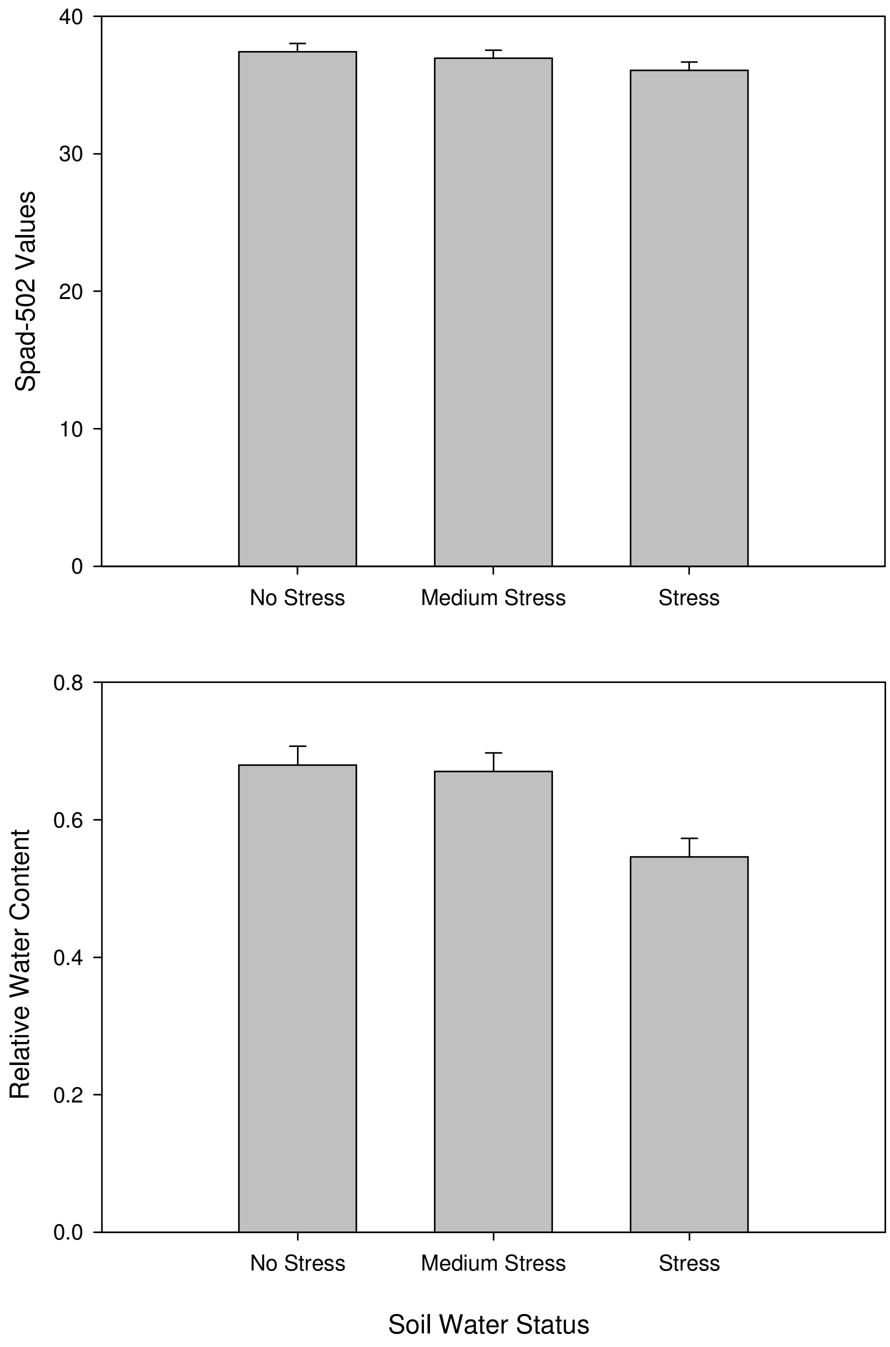

Figure 5.4. Effect of water stress on leaf Spad-502 values and leaf relative water content of grain sorghum in a greenhouse study.

5.6.2 Effect of water and N stresses on leaf spectral reflectance

Water x N rate interaction resulted in significant differences in spectral reflectance in the mid-infrared range (Table 5.1). In general, inadequate water and N caused increased reflectance in the visible, near infrared (NIR) and mid infrared (MIR) regions of spectral profile for grain sorghum (Figs. 5.5A and B).

In sections of green (550 -560 nm), red edge (703 -717 nm) and MIR (1450 -1460 nm and 1760 – 1770 nm), water and N stress significantly affected the spectral reflectance of sorghum leaf (Table 5.1). Many environmental and physiological factors can cause increased leaf reflectance, but N deficiency generally increases reflectance in the green and the red edge ranges (Carter and Knapp, 2001; Daughtry et al., 2000; Zhao et al., 2003). Leaf reflectance in the green, red edge and MIR wavelength of the spectrum can be good indicators of N and water stress in plants (Blackmer et al., 1994, Wooley, 1971; Hunt and Rock, 1989; Penuelas et al., 1994). Reflectance properties of leaves are controlled by the absorption and scattering processes which occur within the leaf. Light is reflected (scattered) at the interface of media with different reflective indexes such as cell wall-air interfaces in the intercellular spaces inside the leaf (Woolley, 1971; Grant, 1987).

Chlorophyll content was generally high with all N rates (0 to 150 kg N ha^{-1}), ranging from 200 to 500 mg m^{-2}. More variability in chlorophyll content has been observed in other studies on maize and wheat which perhaps are more sensitive to N stress (Schepers et al., 1996; Schlemmer et al., 2005). Sorghum leaf reflectance in the green and red edge wavelengths had the best correlation with chlorophyll content with a R^2 value of 0.74, compared with lower R^2 values of 0.21, 0.36 and 0.20 in the blue, red

and NIR wavelength, respectively (Fig. 5.6). There is strong absorption of biochemical pigments for photosynthetic activities in the blue and red spectral region. According to Gitelson (personal communication), even in completely yellow leaves, absorption is higher than 85% in the blue spectral region. Due to high reflectance in the green spectral region, the region is sensitive to wide ranges of chlorophyll content, hence the strong coefficient of determination observed. Sims and Gamon (2002) reported that reflectance around the 700 nm spectral region was the most sensitive indicator of chlorophyll of many non-related leaves and that the ratio of NIR to red edge indices proposed by Gitelson and Merzlyak (1994) could be used as measure of chlorophyll content for many plant species.

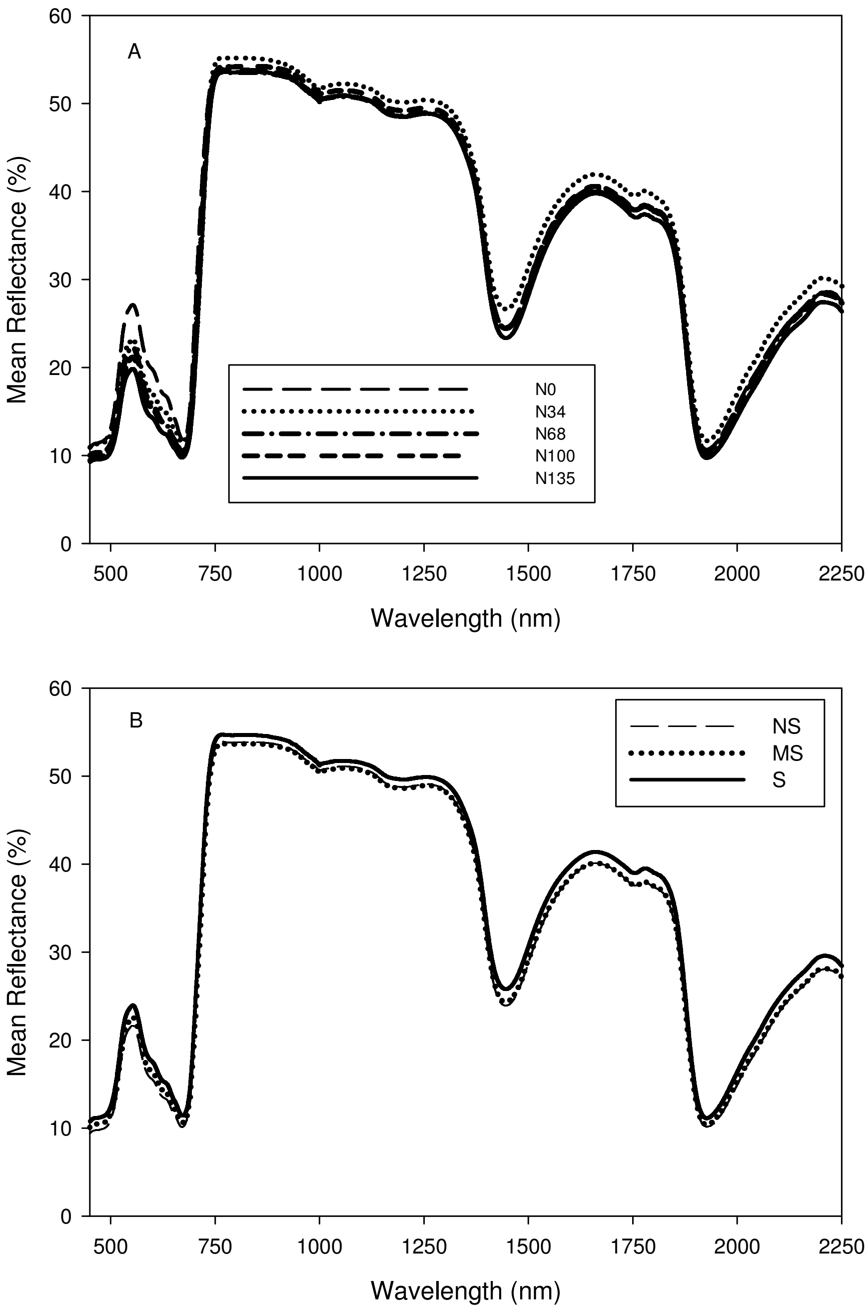

Figure 5.5. Mean reflectance spectrum of grain sorghum leaf at 75 days after sowing in a greenhouse across five N rates (A) and three water levels (B).

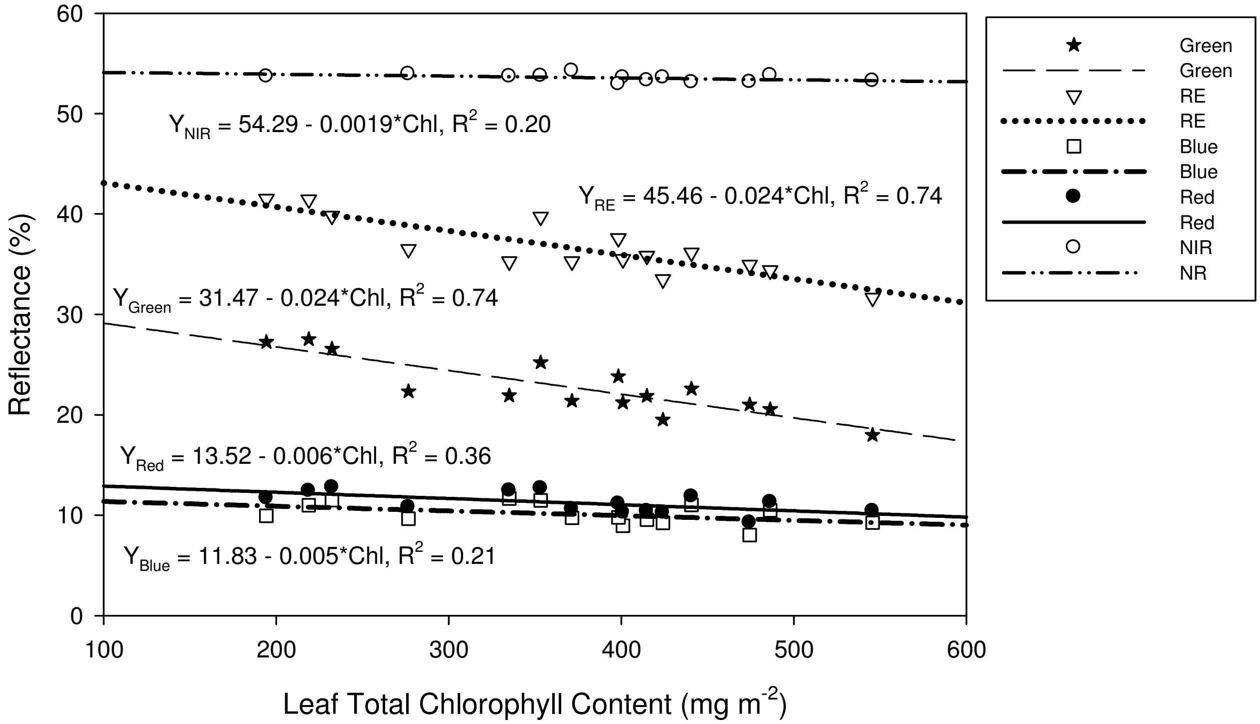

Figure 5.6. Spectral reflectance in the blue, green, red, red edge (RE), and near infrared (NIR) regions plotted against leaf total chlorophyll content of grain sorghum leaves.

5.6.3 Algorithm calibration and validation

Using the concept developed by Gitelson et al. (2003), a model was calibrated and validated with an independent data set for leaf chlorophyll content estimation in grain sorghum in a greenhouse study. According to Gitelson et al. (1996), reciprocal reflectance alone at certain wavelengths could be used to quantitatively estimate chlorophyll content. To be able to select a spectral range that could be used to calibrate a model for leaf chlorophyll content estimation, a linear correlation between chlorophyll

content and spectral reflectance was established. The wavelength with the lowest RMSE and highest R^2 and the wavelength in the NIR regions with the highest RMSE and lowest R^2 were selected for the calibration. In the blue (400 to 500 nm) and red wavelengths (675 to 685 nm), R^2 was lowest (Fig. 5.6) and RMSE was highest in the visible spectral range (Fig. 5.7).

Reciprocal reflectance at 549 to 560 nm ($R[_{(549\text{-}560)}]^{-1}$) with the peak at 550 nm ($R[_{(550)}]^{-1}$) in the green spectral range and from 710 to 718 nm ($R[_{(710\text{-}718)}]^{-1}$) with a peak at 718 nm ($R[_{(718)}]^{-1}$) in the red edge range were selected for model calibration since this relationship had the highest R^2 and lowest RMSE in the spectral profile and agreed with Gitelson et al. (2003). The best fit regressions between chlorophyll contents and the four reflectance indices were linear with a R^2 of 0.76 to 0.79 (Fig. 5.8). According to Gitelson et al. (2003), $R[_{(NIR)}]^{-1}$ values are comparable to chlorophyll content in leaves with very low chlorophyll content and thus represent scattering and non-pigment leaf absorption.

Subtracting $R[_{(NIR)}]^{-1}$ values from the green and RE index slightly improved R^2 values and significantly reduced the intercept of the model from 312 to 35 mg m^{-2} in the green range and from 486 to 21 mg m^{-2} (Table 5.2). Zhao et al. (2005) suggested two narrow ranges centered on $R_{(555)}$ nm and $R_{(715)}$ (± 5) nm for detecting N deficiency in sorghum. They found the ratio of two indices R_{1075}/R_{735} and R_{405}/R_{715} had a better linear relationship than single waveband indices with R^2 values ranging from 0.64 to 0.82.

The normalized difference vegetation index (NDVI) and simple ratio (SR) index (Rouse et al. 1974) are two commonly used vegetative indices in remote estimation of chlorophyll in plants. These two indices and the green NDVI (Gitelson et al., 1996) were compared with reciprocal reflectance indices suggested in this study using the same data

set. Both NDVI and SR performed poorly while GNDVI did better compared to the suggested indices in estimating chlorophyll (Fig. 5.9). Gitelson et al. (2003) reported that indices that use reflectance in the red range were sensitive only to low chlorophyll and not sensitive to moderate to high chlorophyll.

Due to the moderate to high chlorophyll of the data set, reflectance in the red spectral region had a low relationship to chlorophyll (Fig. 5.8), and consequently it was not surprising that both NDVI and SR were poorly related to chlorophyll in this study. The calibrated models were used to predict chlorophyll from an independent second data set collected from the same study. Reciprocal reflectance values in the independent data set were used in the indices of the calibrated model to estimate chlorophyll. The estimated chlorophyll was then compared with measured chlorophyll content. Table 5.3 shows the RMSE and standard error of estimation between the predicted and the measured chlorophyll. The proposed models performed well in predicting chlorophyll, with RMSE ranging from 52 to 56 mg m^{-2} (Table 5.3). As expected both NDVI and SR did poorly with very high RMSE while GNDVI performed better.

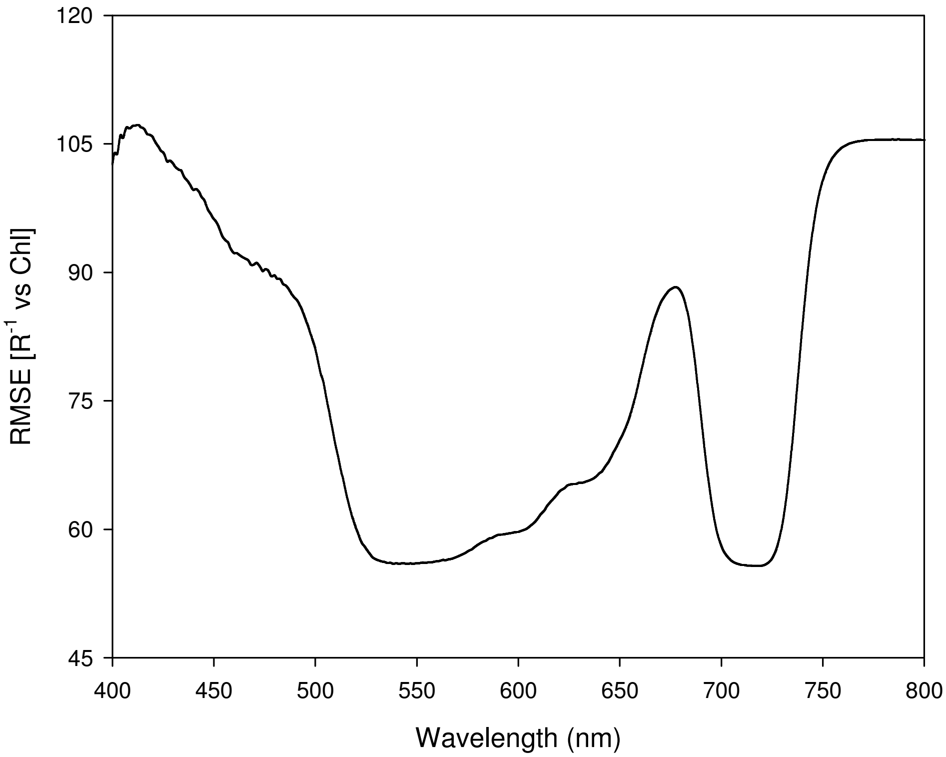

Figure 5.7. The RMSE for the relationship between reciprocal reflectance and leaf chlorophyll content of grain sorghum at 75 days after planting in a greenhouse.

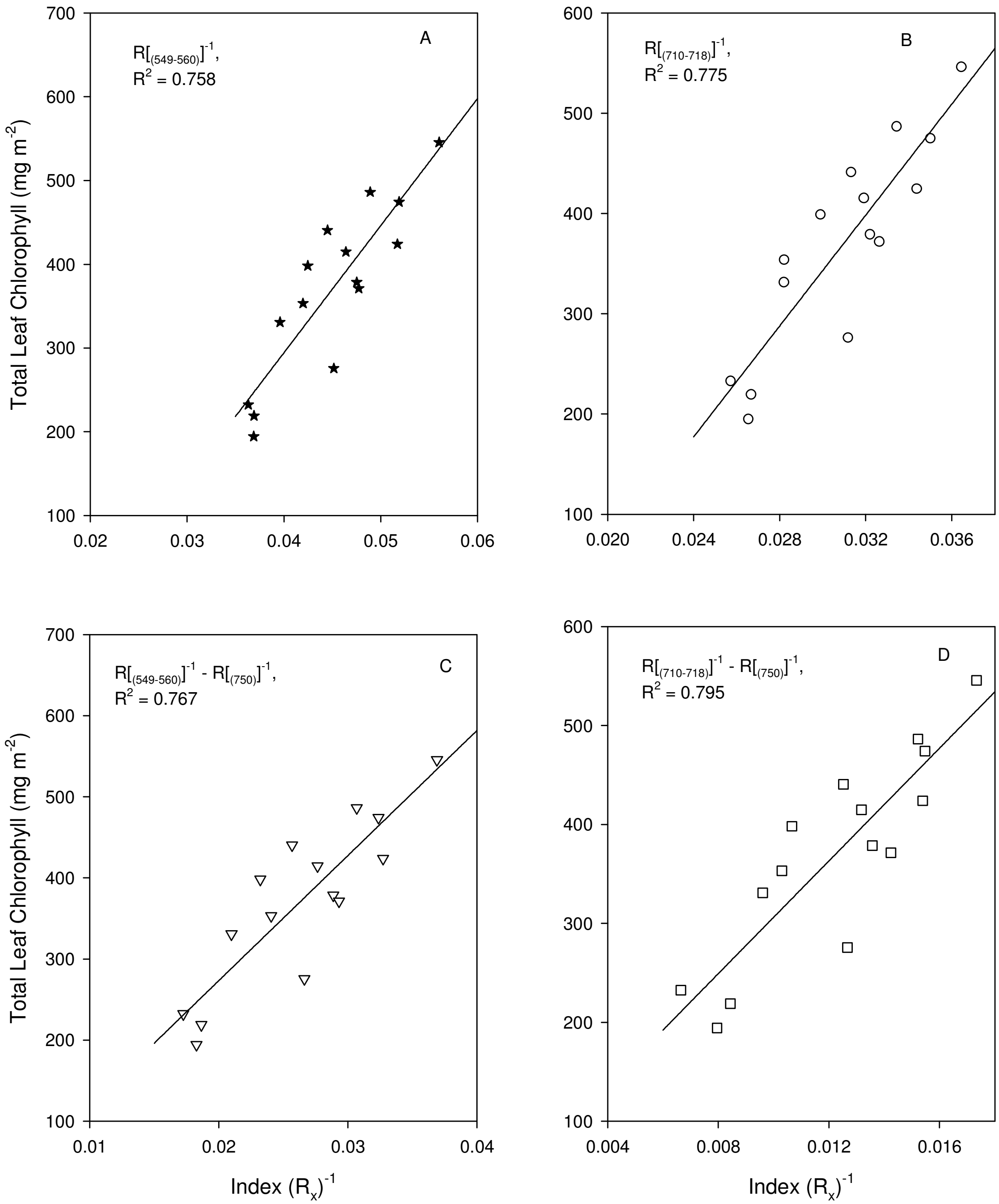

Figure 5.8. Relationship between reflectance index $[R_x]^{-1}$ and leaf total chlorophyll content in the green (A) and RE (B) spectral range, and subtraction NIR ($R[_{(750)}]^{-1}$) from $[R_x]^{-1}$ green (C) and red edge (D).

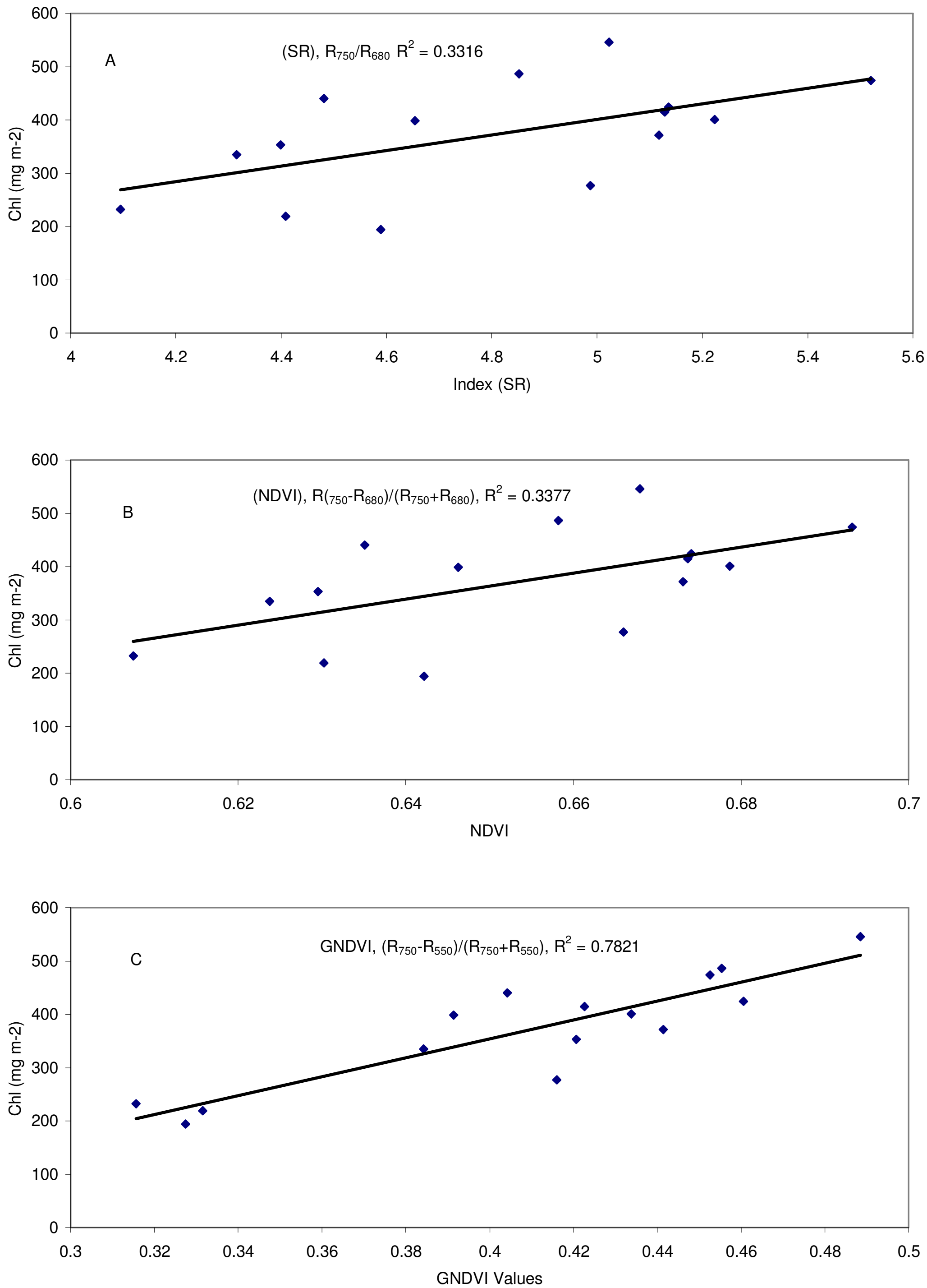

Figure 5.9. Relationship of leaf total chlorophyll concentration with reflectance indices: simple ratio (A), normalized difference vegetation index (B) and green normalized difference vegetation index (C).

Table 5.2. Calibrated models for estimating total leaf total chlorophyll (Chl) content in grain sorghum leaves at 75 days after planting in a greenhouse study.

†R_λ	Model	R^2
$R[_{(549-560)}]^{-1}$	Chl = 15176* R_λ – 312.78	0.77
$R[_{(549-560)}]^{-1} – R[_{750}]^{-1}$	Chl = 15426* R_λ – 35.154	0.77
$R[_{(710-718)}]^{-1} – R[_{750}]^{-1}$	Chl = 27658* R_λ - 486.54	0.78
$R[_{(710-718)}]^{-1} – R[_{750}]^{-1}$	Chl = 28484* R_λ - 21.317	0.80
SR, R_{750} / R_{680}	Chl = 146.27* R_λ - 330.32	0.33
NDVI, $R[_{(750-680)}/ R_{(750+680)}]$	Chl = 2445.9* R_λ - 1226.7	0.34
GNDVI, $R[_{(750-550)}/ R_{(750+550)}]$	Chl = 1769.5* R_λ - 353.96	0.78

† Reflectance index.

Table 5.3. Relationship between predicted and measured total leaf chlorophyll (Chl) content using calibrated models developed from an independent data set.

†R_λ	Model	RMSE (mg m^{-2})	SE
$R[_{(550-560)}]^{-1}$	Chl_{pred} = 0.7349*R_λ + 107.91	53.0	48.7
$(R[_{(550-560)}]^{-1}- R[_{(750)}]^{-1}$	Chl_{pred} = 0.7197* R_λ + 112.21	53.6	48.8
$R[_{(710-717)}]^{-1}$	Chl_{pred} =0.7023* R_λ + 124.66	52.4	44.4
$R[_{(710-717)}]^{-1}- R[_{(750)}]^{-1}$	Chl_{pred} = 0.6728* R_λ + 133.28	54.0	45.1
SR [R_{780}/R_{685}]	Chl_{pred} = 0.3099* R_λ + 262.59	92.3	67.4
NDVI [(R_{780} - R_{685})/(R_{780} - R_{685})]	Chl_{pred} = 0.3134* R_λ + 259.63	90.4	65.8
GNDVI[(R_{750}-R_{550})/(R_{750}-R_{550})]	Chl_{pred} = 0.7237* R_λ + 101.18	56.0	52.6

† Reflectance index.

5.6.4 In-field canopy reflectance

A model to remotely estimate grain sorghum canopy chlorophyll (CChl) content in a field study was calibrated using the same approach as discussed in the greenhouse study. Canopy chlorophyll content ranged from 0.8 to 1.6 g m^{-2} and was significantly influenced by N rate x row configuration interaction (Fig. 5.10). Increased N rate resulted in higher LAI and higher biomass yield which led to increased canopy chlorophyll.

Canopy chlorophyll with conventional planting configuration (s0) was significantly higher than with skip-row planting configurations (Fig. 5.11B). This may be attributed to the large LAI of s0 (Fig. 5.10). Conventional planting configuration had the highest canopy chlorophyll and the lowest reflectance and the highest N applied treatment had highest canopy chlorophyll and lowest canopy reflectance (Fig. 5.11).

Linear correlation between canopy chlorophyll and reciprocal reflectance indicated that the reciprocal reflectance in the green wavelength (553 to 563 nm) and in the RE wavelength (703 – 709 nm) had the least RMSE and highest R^2 (Fig. 5.12). Four indices were calibrated using reciprocal reflectance in the green ($R[_{(553\text{-}563)}]^{-1}$ and RE ($R[_{(703\text{-}709)}]^{-1}$ wavelengths and compared to GNDVI (Gitelson et al., 1996) which performed well with the greenhouse data. Unlike models calibrated for leaf Chl content, all indices had quadratic relationships with canopy chlorophyll, with coefficients of determination ranging from 0.68 to 0.78 (Table 5.4). Collier (1989) attributed the observed differences between leaf and canopy reflectance to factors such as changes in canopy geometry and leaf area index. Soil and background reflectance can have a greater effect on reflectance than the physiological and anatomical changes in leaves caused by stress.

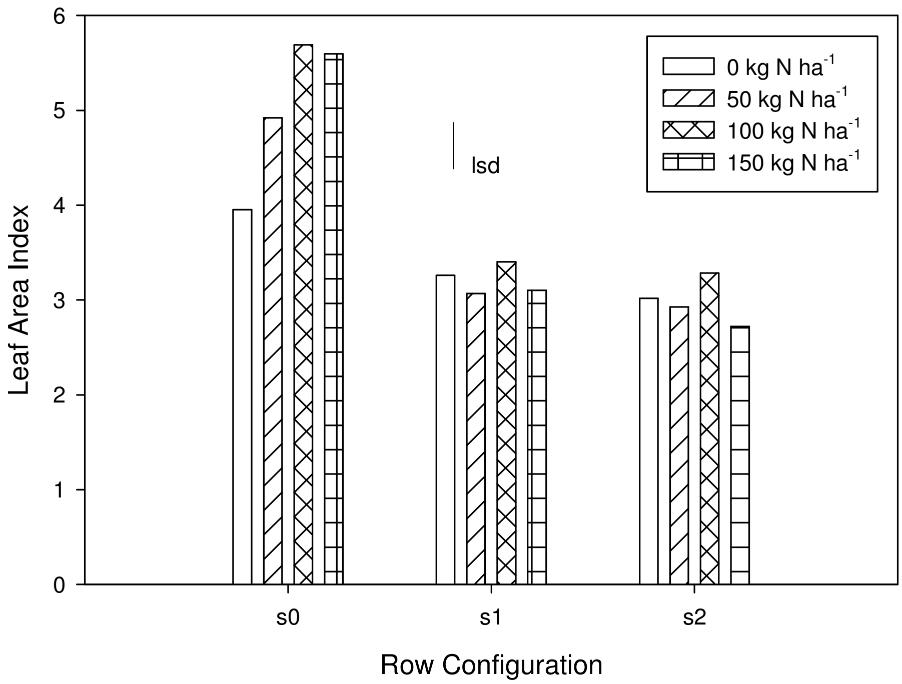

Figure 5.10. Interaction effect of four N rates of 0, 50, 100 and 150 kg N ha^{-1} and three planting configurations on leaf area index of grain sorghum canopy. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped. Y-bars = LSD = 0.05.

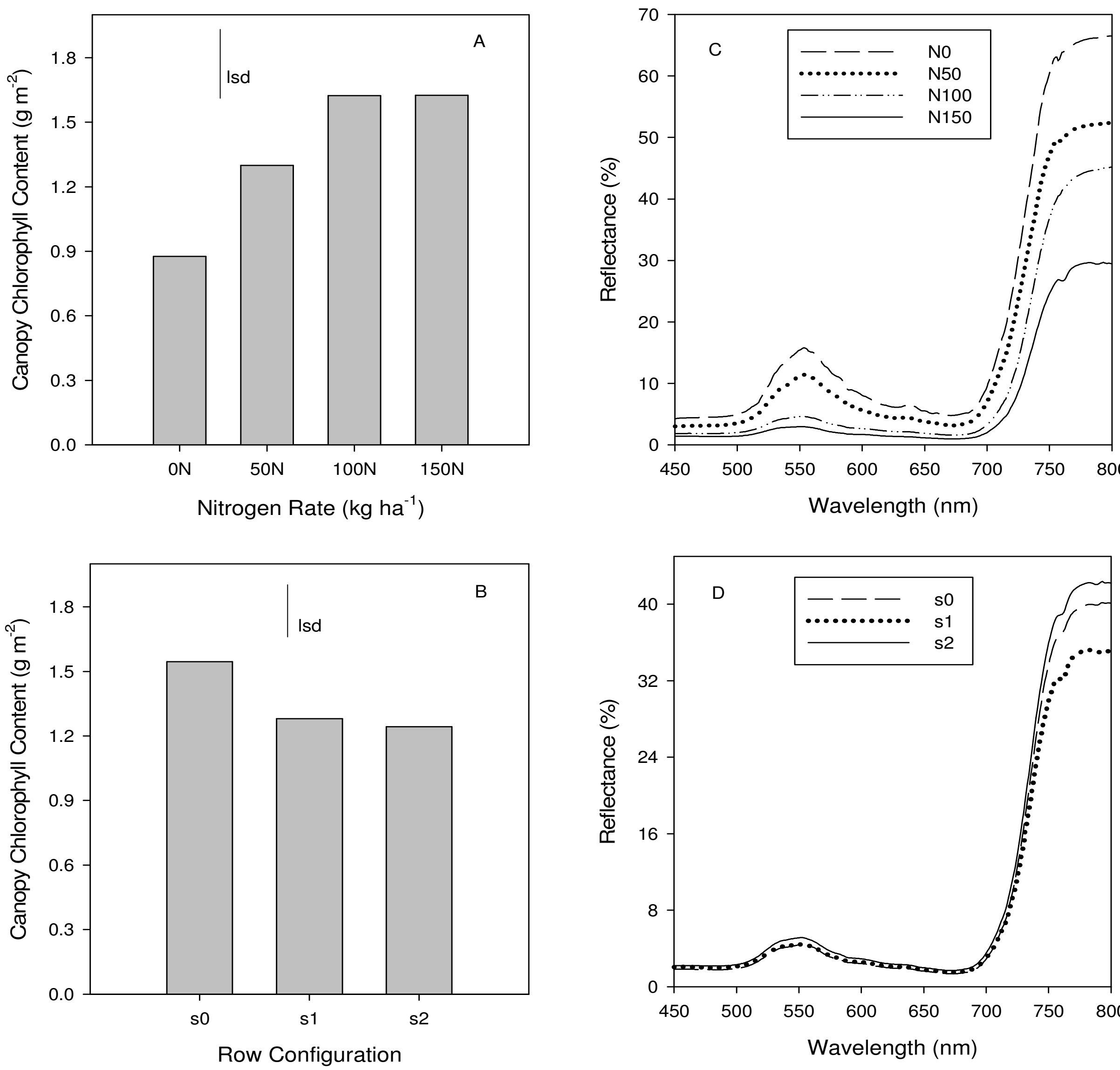

Figure 5.11. Effect of four N rates (A) of 0, 50, 100 and 150 kg N ha^{-1} and three row configurations (B) on mean total leaf chlorophyll concentration (A and B), and mean reflectance (C and D) of grain sorghum canopy. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped. Y-bars = LSD = 0.05.

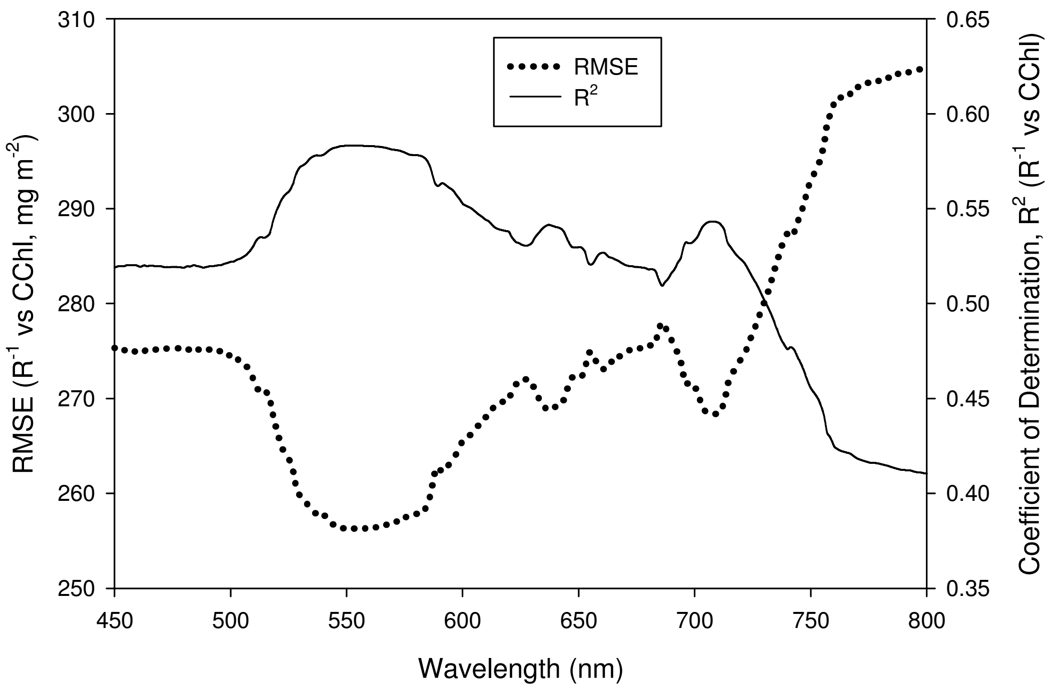

Figure 5.12. RMSE (dotted line) and coefficient of determination (solid line) of the relationship between reciprocal of reflectance and canopy chlorophyll content at 75 days after planting at South Central Agricultural Laboratory, Nebraska.

Table 5.4. Calibration of indices for canopy chlorophyll content in the field 75 days after planting at South Central Agricultural Laboratory, Nebraska.

Index (x)	Model	R^2
$R[_{(553\text{-}563)}]^{-1}$	$-40.2053*x^2 + 4.271*x + 0.7184$	0.70
$R[_{(703\text{-}709)}]^{-1}$	$-2.8622*x^2 + 3.8878*x + 0.6964$	0.78
$R[_{(553\text{-}563)}]^{-1} - R[_{(800)}]^{-1}$	-4.7755*x2 + 4.4171*x + 0.7758	0.69
$R[_{(703\text{-}709)}]^{-1} - R[_{(800)}]^{-1}$	$-3.825*x^2 + 4.2729*x + 0.7336$	0.78
GNDVI	$-1240.9*x^2 - 2412.9*x - 1171.2$	0.68

5.7 Conclusion

With adequate plant water status, both Spad-502 values and extracted chlorophyll content had linear relationships with N application rate. Under water stress conditions, there is the tendency for Spad-502 to under-estimate the N status of the plant. Leaf and canopy reflectance of grain sorghum was reduced by both N and water stress. Reciprocal reflectance of 549 to 560 nm, $R[_{(549\text{-}560)}]^{-1}$ with the peak at 550 nm, $R[_{(550)}]^{-1}$ and 710 to 718 nm, $R[_{(710\text{-}718)}]^{-1}$ with peak at 718 nm, $R[_{(718)}]^{-1}$ minus reciprocal reflectance in the NIR, $R[_{(750)}]^{-1}$ had a linear relationship with chlorophyll. This model predicted leaf total chlorophyll with less RMSE than other models in literature. At the canopy level, the relationship between the model and canopy chlorophyll was quadratic, with the best model having a R^2 of 0.78.

5.8 References

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APPENDICES

Table 2A. Summary of analysis of variance of 100 kernel weight (g) of grain sorghum with three row configurations and two plant populations at ten site-years across Nebraska.

		Clay 2005	Clay 2006	Clay 2007	Gosper 2006	Frontier 2006	Hayes 2006	Cheyenne 2006	Cheyenne 2007	Lincoln 2007	Red W. 2007
Source	DF	----------	----------	----------	----------	Mean square	----------	----------	----------	----------	----------
Row Config (RC)	2	0.074ns	0.098**	0.330**	0.088ns	0.029ns	0.038ns	0.041ns	0.001ns	0.90ns	0.043ns
Plant Pop (PP)	1	0.014ns	0.002**	0.222*	0.0001ns	0.008ns	0.136ns	0.037ns	0.004ns	0.013ns	0.0001ns
RC x PP	2	0.010ns	0.0003ns	0.035ns	0.026ns	0.033ns	0.033ns	0.038ns	0.003ns	0.029ns	0.002ns
Residual	15†	0.030	0.008	0.050	0.039	0.012	0.044	0.022	0.003	0.036	0.017

† Residual DF at the Clay county site in 2006 and 2007 = 46, remaining site-years = 15.

* $P \leq 0.05$, ** $P < 0.01$; ns = not significant at $P = 0.05$.

Table 2B. Summary of analysis of variance of grain yield per panicle (g) of grain sorghum with three row configurations and two plant populations at ten site-years across Nebraska.

		Clay 2005	Clay 2006	Clay 2007	Gosper 2006	Frontier 2006	Hayes 2006	Cheyenne 2006	Cheyenne 2007	Lincoln 2007	Red W. 2007
Source	DF	----------	----------	----------	----------	Mean square	----------	----------	----------	----------	----------
Row Config. (RC)	2	2.57ns	12.25ns	481**	10.74ns	262.7*	369.4**	239.3*	69.44ns	2379**	86.09ns
Plant Pop (PP)	1	149.2*	1292**	3142**	3.34ns	612.4**	158.5ns	66.85ns	19.62nn	160.3ns	301.0ns
RC*PP	2	293.2**	62.57ns	176.7ns	405.3ns	19.31ns	71.57ns	111.3ns	96.25ns	156.0ns	67.45ns
Residual	15†	84.81	29.29	95	143.1	54.65	42.51	61.62	95.27	266.3	111.3

† Residual DF at the Clay county site in 2006 and 2007 = 46, remaining site-years = 15.

* $P \leq 0.05$, ** $P < 0.01$; ns = not significant at $P = 0.05$.

Table 2C. Summary of analysis of variance of panicles m^{-2} of grain sorghum with three row configurations and two plant populations at ten site-years across Nebraska.

		Clay 2005	Clay 2006	Clay 2007	Gosper 2006	Frontier 2006	Hayes 2006	Cheyenne 2006	Cheyenne 2007	Lincoln 2007	Red W. 2007
Source	DF	------------------				Mean square					------------------
Row Config (RC)	2	1188**	155**	177.5**	73.29*	14.3ns	0.292ns	1.542ns	3137.8**	3.292ns	2.303ns
Plant Pop (PP)	1	341**	62.3**	337.6**	28.17ns	84.4ns	35.04*	22.04**	1666.7**	2.667ns	0.634ns
RC*PP	2	66**	10.1ns	33.73**	85.54*	27.9ns	7.04ns	5.542**	358**	9.042ns	0.203ns
Residual	15†	7.88	3.64	5.81	19.06	23.4	5.74	0.619	43.64	19.49	22.8

† Residual DF at the Clay county site in 2006 and 2007 = 46, remaining site-years = 15.

* $P \leq 0.05$, ** $P < 0.01$; ns = not significant at $P = 0.05$.

Table 2D. Summary of analysis of variance of number of kernels panicle^{-1} of grain sorghum with three row configurations and plant populations at ten site-years across Nebraska.

		Clay 2005	Clay 2006	Clay 2007	Gosper 2006	Frontier 2006	Hayes 2006	Cheyenne 2006	Cheyenne 2007	Lincoln 2007	Red W. 2007
Source	DF	Mean square									
Row Conf.	2	67862	70562	401549	7966	416413	517988	215480	77065	3114976	164027
(RC)		ns	ns	ns	ns	*	*	ns	ns	**	ns
Plant Pop	1	1026035	2543573	3819902	10792ns	914315	1138110	24313	43109	134693	332877
(PP)		**	**	**		**	*	ns	ns	ns	ns
RC*PP	2	32043ns	87421	217878	1001828	56294	29647	543534	143655	117972	95761
			ns	ns	ns	ns	ns	*	ns	ns	ns
Residual	15†	64259	50666	152185	404957	90535	147503	143419	118765	499119	163716

† Residual DF at the Clay county site in 2006 and 2007 = 46, remaining site-years = 15

* $P \leq 0.05$, ** $P < 0.01$; ns = not significant at $P = 0.05$.

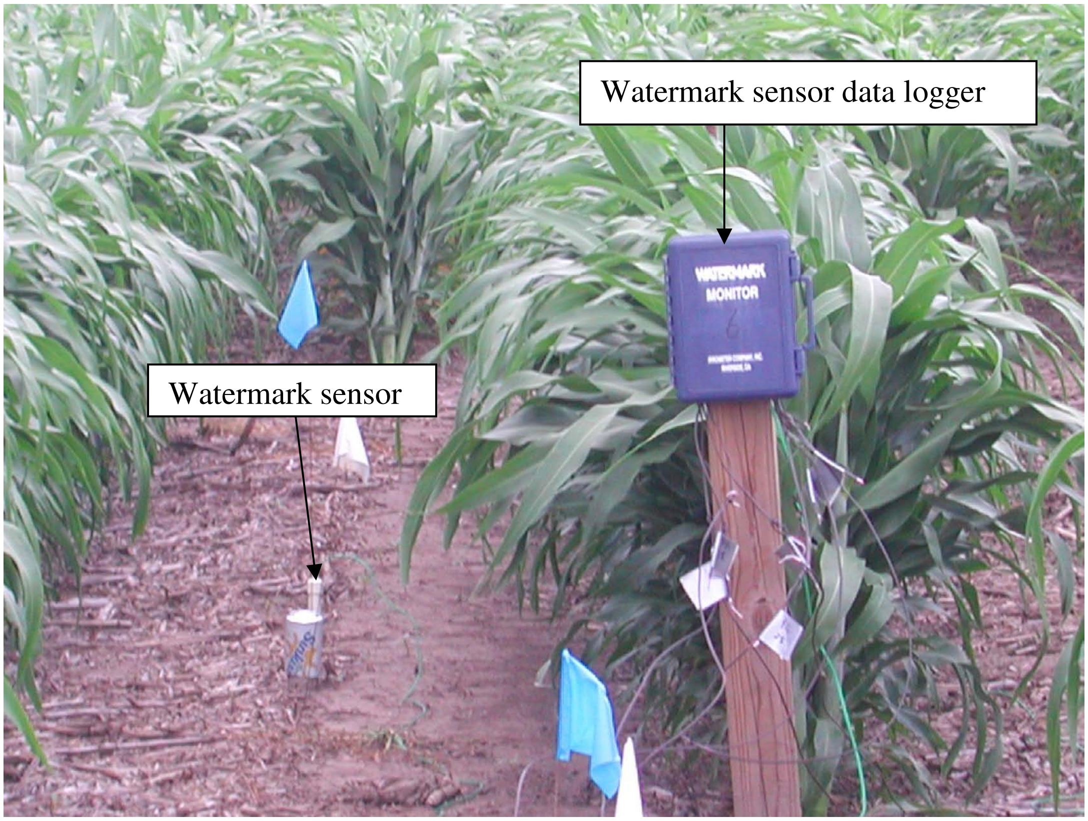
Table 4A. Analysis of variance summary of grain sorghum leaf chlorophyll with three row configurations and two seeding rates in 2005 at South Central Agricultural Laboratory, UNL, Nebraska.

		41	57	68	75	89	103
		---------------------Days after planting-------------------------					
	DF	---------------------Mean square---------------------------------					
Row Config. (RC)	2	117.5ns	5537ns	4614.5ns	2491.9ns	68787**	99441**
Plant pop (PP)	1	55.1ns	2036ns	9513.3ns	5845.8ns	13316ns	791.9ns
RC*PP	2	175.9ns	4622ns	9191ns	4686.7ns	1473.8ns	2909ns
Residual	39	2472	6809	7338.7	7006.3	4743.8ns	4214

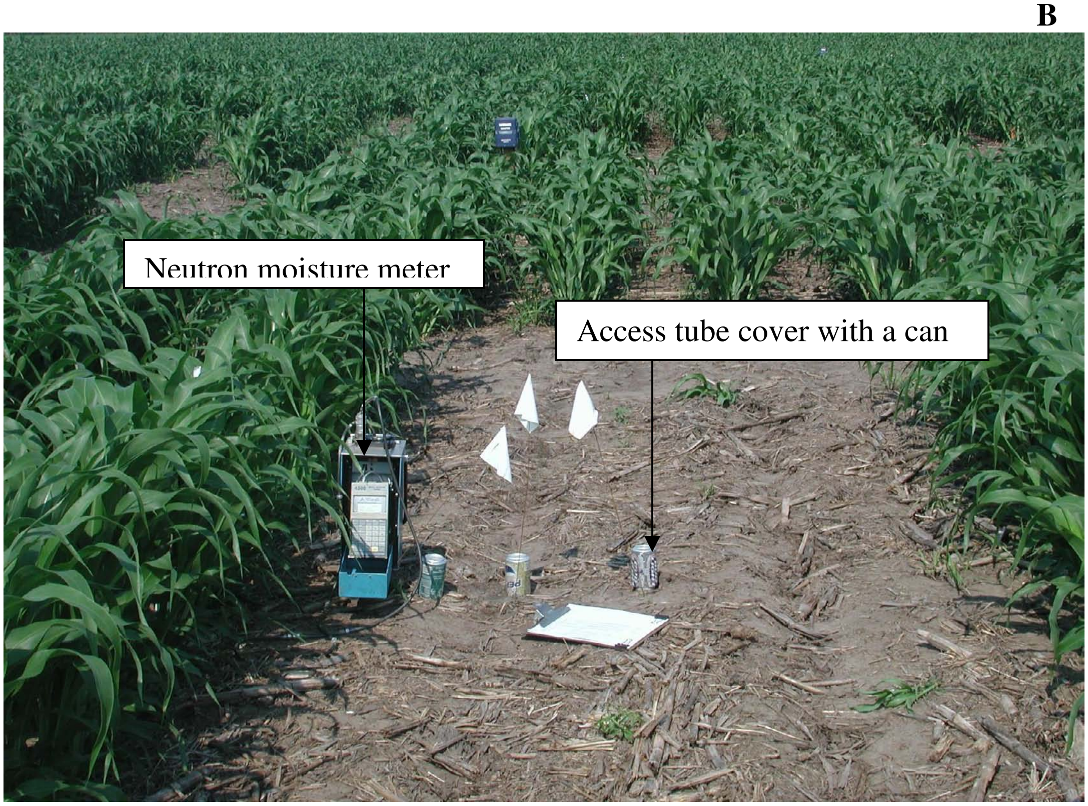
Figure 2A. Conventional configuration, (solid planting) s0.

Figure 2B. Plant every other row, (single skip configuration) s1.

Figure 2C. Plant 2 rows and skip two rows, (double skip configuration) s2.



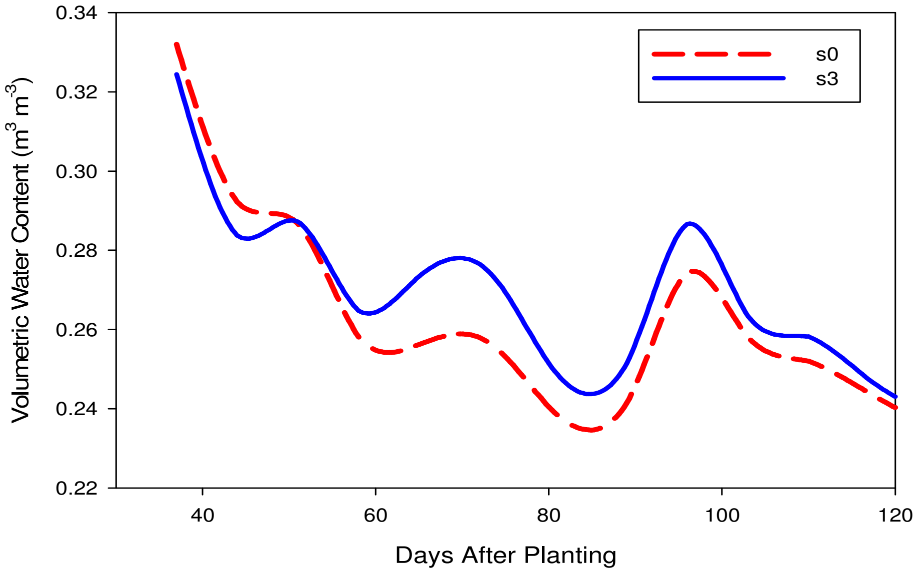
B



A

Figure 2D. Plot depicting the location of neutron probe access tubes and neutron moisture meter (A), and Watermark sensors and Watermark sensor data logger (B).

Figure 2E. Canopy temperature and relative humidity sensor in a row.



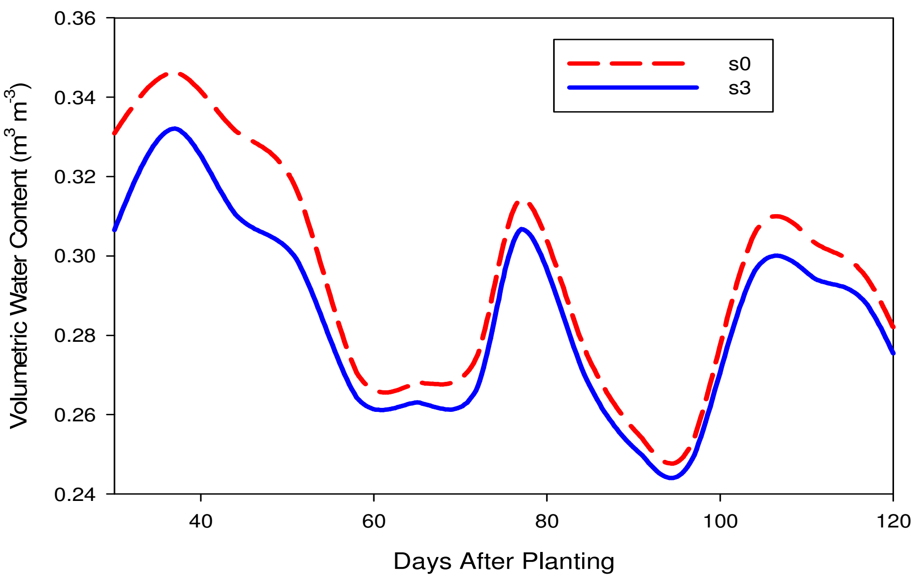


Figure 3A. Soil water content at 450 mm depth recorded by Watermark sensor placed at the center of inter-row area in the conventional (s0) and double skip (s2) configurations in 2005 and 2006 under grain sorghum at Clay Co., Nebraska. Data logged every 30 minutes.

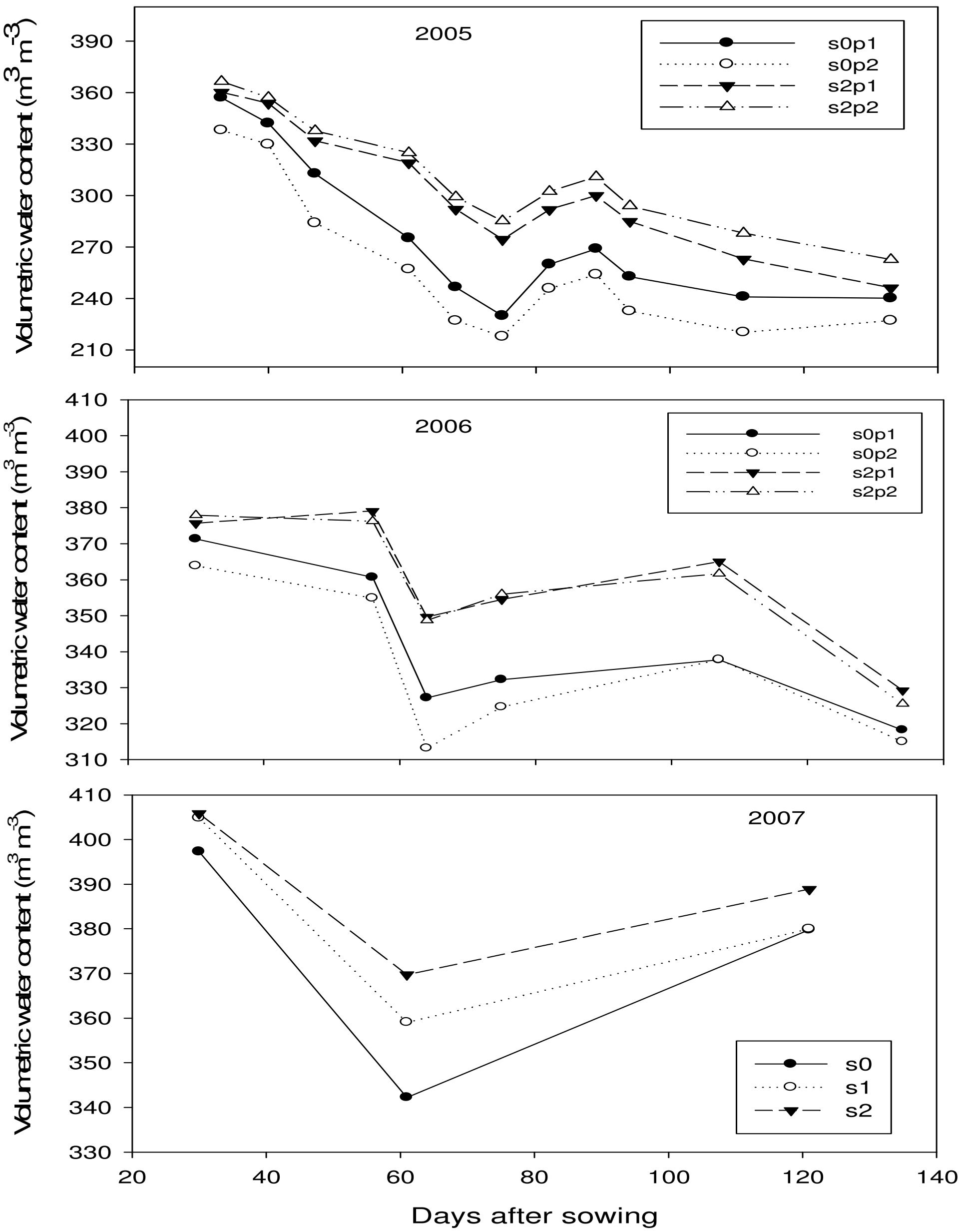


Figure 3B. Soil water content at the mid-point of the inter-row area measured weekly to 1200 mm depths as influenced by three row configurations and two plant populations at Clay Co. in 2005 and 2006 and row configuration in 2007. s0 = conventional planting with all rows planted, s2 = two rows planted alternate with two rows skipped, p1 = 75000 plants ha^{-1}, p2 = 150000plants ha^{-1}.

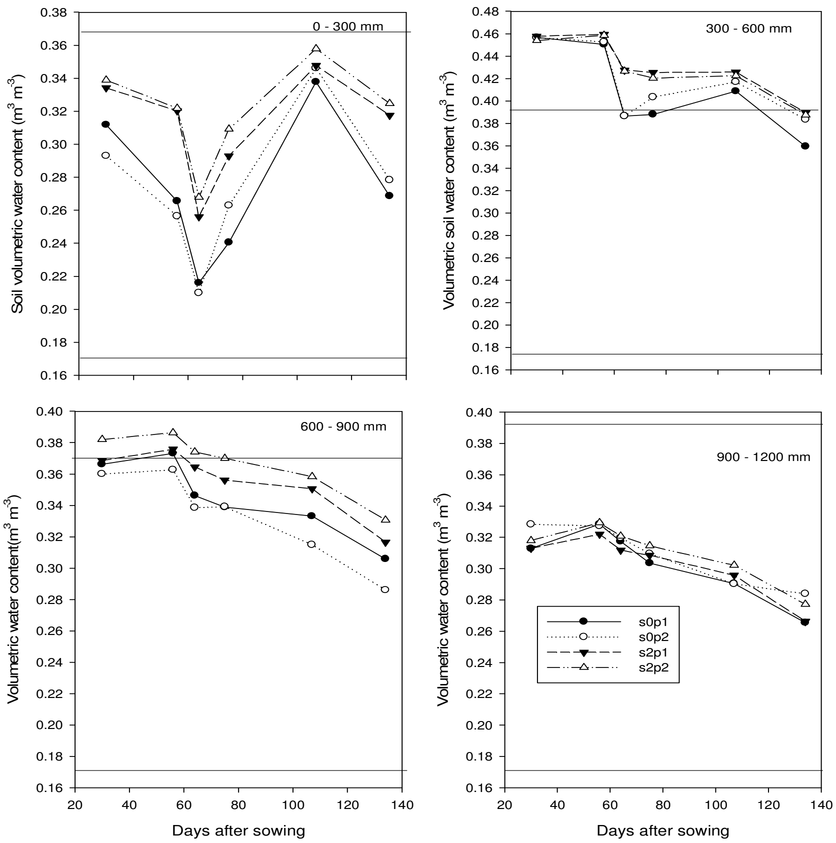


Figure 3C. Volumetric soil water content at four soil depths measured from the center of the skipped area at the Clay Co. site in 2006 as influenced by row configuration and plant population of 75000 and 150000 plants ha^{-1}. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped. p1 = 75000 and p2 = 150000 plant ha^{-1}. Upper horizontal line = field capacity (FC), lower horizontal line = permanent wilting point (PWP).

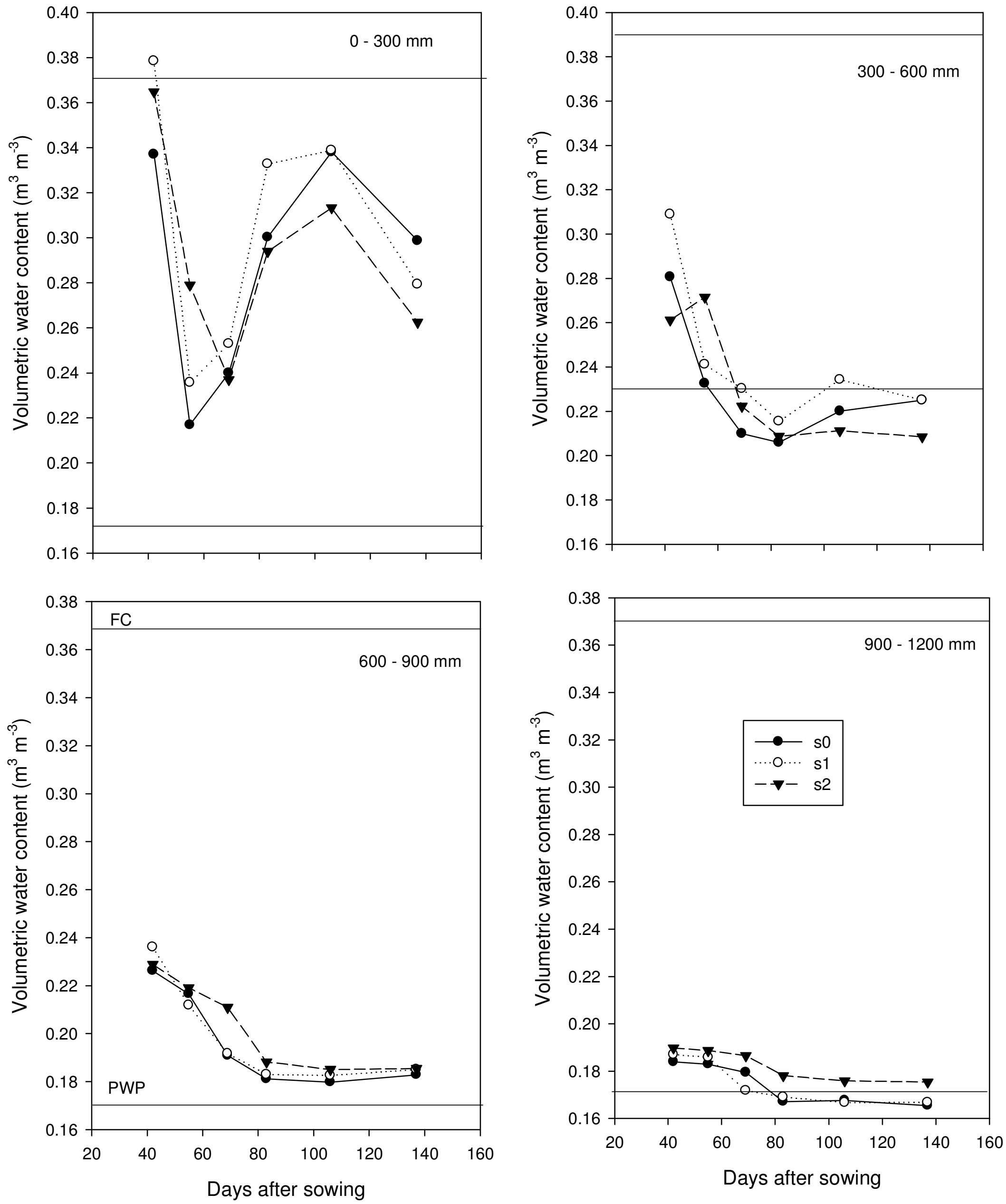


Figure 3D. Volumetric soil water content at four soil depths at Gosper as influenced by row configuration two plant population 50000 (p1) and 100000 (p2) seeds ha^{-1}. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped. Upper horizontal line = field capacity (FC), lower horizontal line = permanent wilting point (PWP).

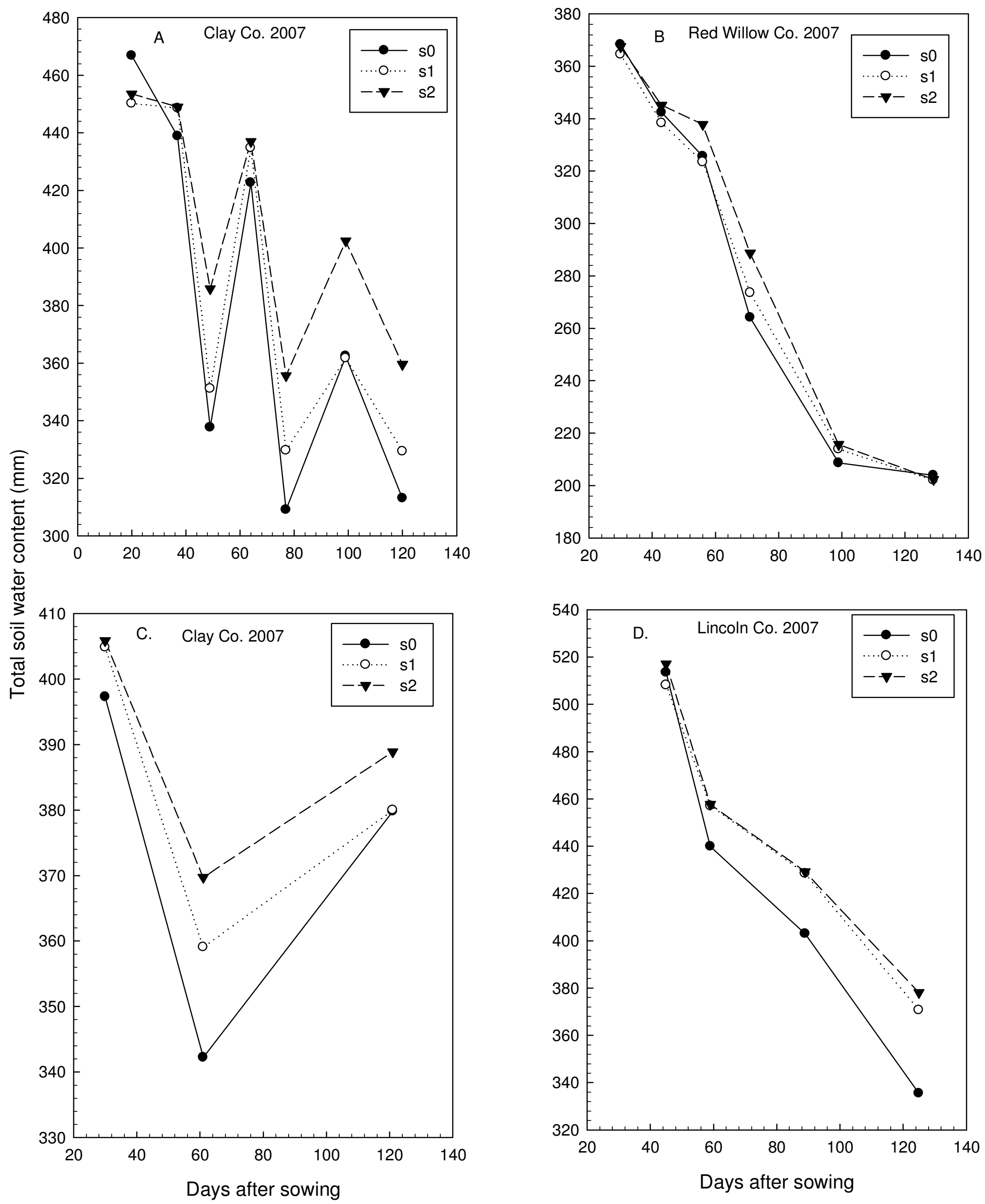


Figure 3E. Total soil water content measured at the center of the inter-row area in a 1200 mm depth under grain sorghum at four site years in Nebraska as affected by row configuration. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped.

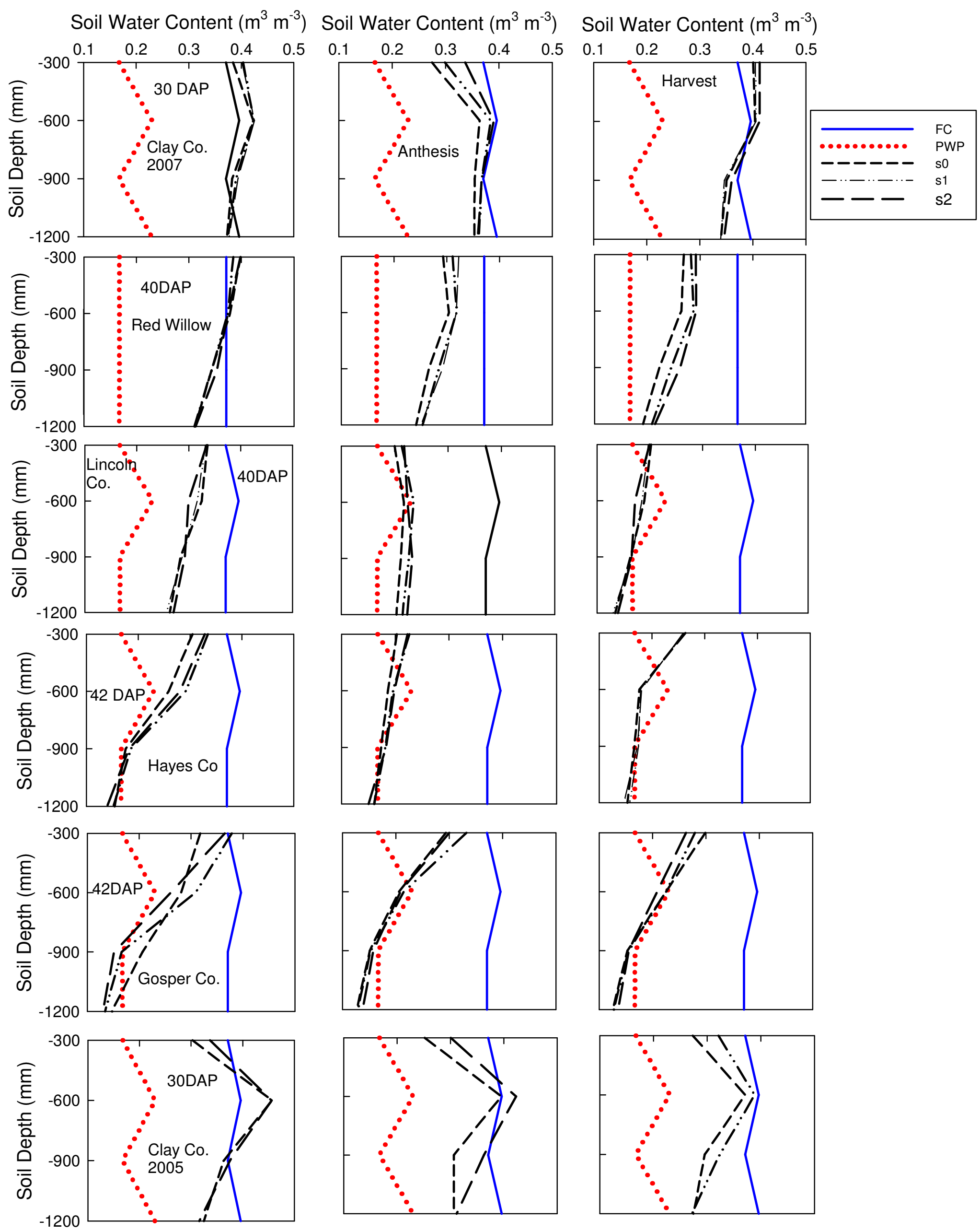


Figure 3F. Soil water content in a profile under three row configurations at first measurement after sowing, anthesis and harvest for six site-years at Nebraska. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted with two rows skipped. Upper horizontal line = field capacity (FC), lower horizontal line = permanent wilting point (PWP).

Figure 5A. A greenhouse study with five rates of N and three water levels on sorghum spectral reflectance.

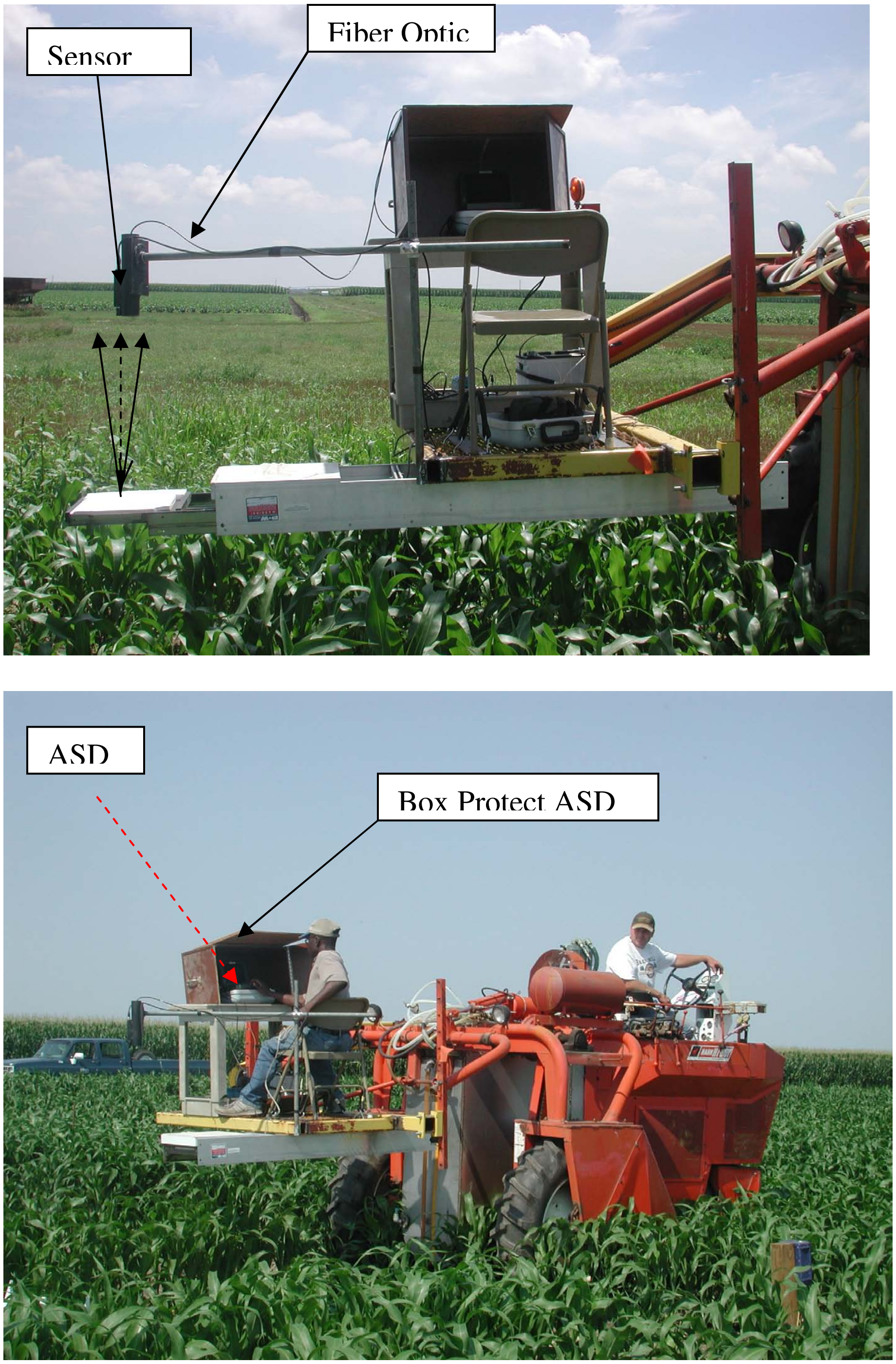


Figure 5B. Analytical Spectral Device mounted on a High-Boy. Three canopy readings were taken per plot at flag leaf stage.