Grain sorghum nitrogen use as affected by planting practice and nitrogen rate

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Abstract

Water and nitrogen supply are often the most critical factors limiting growth and yield in crop production. A study was carried out in 2006 and 2007 to determine N use efficiency of grain sorghum (*Sorghum bicolor* (L.) Moench) in dryland production at the University of Nebraska, Lincoln, Nebraska, South Central Agricultural Laboratory. The study evaluated three row planting arrangements (RPA) including all rows planted (s0), alternate rows planted (s1), and two rows planted alternated with two skipped rows (s2) in a complete factorial with plant populations (PP) of 75,000 and 150,000 plants ha⁻¹ and 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, magnitude of N uptake, and N use efficiency (NUE) for grain sorghum under dryland conditions with different row configurations. Conventional planting out-yielded skip-row planting by 23 to 36% in each year. Percent N translocated from biomass to grain at physiological maturity at half bloom ranged from 29 to 35% in 2006 compared with 46 to 51% in 2007. The RPA x PP interaction affected internal NUE (IEN) in 2006 and 2007, and physiological NUE (PEN) in 2006. The RPA x N rate interaction affected partial factor productivity (PFPN) in 2006.

Keywords: Agronomic, grain sorghum, nitrogen use efficiency, productivity.

1. Introduction

Grain sorghum is tolerant of soil water deficits and efficient in soil nutrient uptake due to its fibrous root system. However, sorghum yield potential can be substantially reduced when water and N are limited. Nitrogen uptake by sorghum is affected by several factors including N availability, soil water availability, soil organic matter, soil chemical and physical properties, previous crop, and genotype (Wortmann *et al.*, 2007; Gardner *et al.*, 1994).

Sorghum is typically grown under dryland conditions and soil water deficits increase the risk of yield loss potential and limits yield response to fertilizer application. Nitrogen deficiencies can reduce water use efficiency due to reduced yield potential and greater soil evaporation (Fisher and Turner, 1979). In highly variable environments inherent to dryland cropping systems, variable N mineralization from soil organic matter and crop residues challenges prediction of an optimal N application rate (Schlegel *et al.*, 2005).

Nitrogen fertilizer recommendations for conventional planting in Nebraska are based on yield goals, soil organic matter level, and residual soil nitrate-N (Shapiro *et al.*, 2009). To improve soil water availability and avoid water stress, skip-row configurations have been used elsewhere with success (Routley *et al.*, 2003; Abunyewa *et al.*, 2010; Abunyewa *et al.*, 2011). Different row configurations may influence plant canopy architecture, root distribution, N and water availability, uptake and utilization (Routley *et al.*, 2006).

A key component in 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). Nitrogen use efficiency has several components such as recovery and agronomic efficiency (Dobermann 2005; Mosier *et al.*, 2004; Cassman *et al.*, 2002). Improving NUE is important

to reduce the cost of producing a crop since N is a costly crop production input.

The objectives of this study were to evaluate the effects of row planting arrangement, N rate and plant population on sorghum grain yield and N use efficiency in a rain-fed environment.

2. Materials and Methods

The study was conducted in 2006 and 2007 at the University of Nebraska-Lincoln, South Central Agricultural Laboratory (SCAL) near Clay Center, Nebraska (lat.40o34'N; long 98o08; 543 m elevation). The study evaluated three row planting arrangements and two plant populations with different N rates arranged as a randomized complete block design with four replications. Row planting arrangement (RPA) included the common practice of all rows planted with 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 rows skipped (s2). Each year, sorghum was sown at a site planted to corn in the previous year.

Plots were seeded and thinned after emergence to the final populations of 75,000 and 150,000 plants ha⁻¹. During each year a medium (110 days) maturing grain sorghum 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). Nitrogen was applied at rates equivalent to 0, 50, 100 and 150 kg N ha⁻¹ as urea in both years. A basal rate of P equivalent to 40 kg ha⁻¹ was applied as triple super phosphate to all plots.

Weeds were controlled with pre-emergence herbicides and post-emergence herbicide eight weeks after

planting at labelled rates using a tractor-mounted boom sprayer. Hand-weeding was also done as necessary throughout the growing seasons to reduce weed pressure.

In-season precipitation, reference evapotranspiration with alfalfa (ETR), solar radiation, wind speed, air temperature and relative humidity during the growing season and 20-year average weather data were obtained 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).

Plots were machine harvested and grain yield determined from 18.2 m² (3.04 by 6 m) in the center of plots of the s0 and from 9.1 m² (1.52 by 6 m) in the center of plots of the skip-row configurations. Yields were adjusted to 135 g kg⁻¹ water concentration by drying a grain subsample at 65 °C over 72 h for dry matter determination. Oven-dried sub-samples of stover and grain were analyzed for N concentration. Stover and grain N uptake were calculated by multiplying the dry weight of stover and grain by the N concentration.

Five components of NUE (Cassman *et al.*, 2002; Baligar *et al.*, 2001) were calculated:

i. Partial factor of productivity for N fertilizer (PFP_N), defined as grain yield (Yg) per unit N applied $PFP_N = YgNr * Nr^{-1}$,

where: Nr is nitrogen applied at a particular rate

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

$$AE_N = (YdNr - YdN0) * Nr^{-1},$$

where Yd is dry matter yield and

N0 is zero N application

iii. Crop internal efficiency (IE_N), defined as grain yield (Yg) over total N uptake (Nu) in the above ground biomass at physiological maturity

$$IE_N = YgNr * (NuNr)^{-1},$$

iv. Physiological efficiency (PE_N), defined as change in grain yield per unit change in N accumulation or N uptake (Nupt) in above ground biomass $PE_N = (YgNr - YgN0) * (NuNr - NuN0)^{-1}$,

v. Fertilizer N recovery efficiency (RE_N), also referred to as NUE (Ortega *et al.*, 2016) in above ground biomass at physiological maturity is defined as change in N uptake per unit N applied

$$RE_N = (NuNr - NuN0) * Nr^{-1}.$$

Statistical analyses

Statistical analyses were performed using PROC MIXED procedure of SAS 9.1 (SAS Institute, 2007). Planting arrangement and N rates were treated as fixed effects, and replication was treated as a random effect. Fisher's protected LSD test was used to separate treatment means at $P \leq 0.05$.

3. Results

3.1. 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. The soil at the 2006 site had lower nitrate (1.26 mg kg⁻¹) than that of 2007 site (4.80 mg kg⁻¹) but higher zinc at 2006 site (1.60 mg kg⁻¹) than that of 2007 (0.34 mg kg⁻¹), while the remaining measured parameters such as organic matter, available phosphorus and exchangeable potassium were similar.

3.2. 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 evapotranspiration (ET) over precipitation, referred to

as climatic deficit (Olufayo *et al.*, 1996) was higher in 2006 (-207 mm) and 2007 (-164 mm) at vegetative stage than -106 mm and -107 mm half bloom stage, for 2006 and 2007, respectively.

3.3. Stover and grain yield

Mean stover yield over N rate was 15.5 and 13.7 Mg ha⁻¹ in 2006 and 2007, respectively, and mean grain yields over N rate was 9.2 and 10.6 Mg ha⁻¹ in 2006

Figure 1. Effect of three row planting arrangement on stover (A) and grain (B) yield at physiological maturity in south-central Nebraska, 2006 and 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).

and 2007, respectively. Stover yield at physiological maturity was not affected by the interaction between row planting arrangement (RPA) and plant population (PP). However, interactions between RPA and N rate affected grain yield in both 2006 and 2007.

Stover and grain yield averaged across N rate were affected by RPA in all years. Conventional row planting out-yielded skip-row planting in stover and grain in all the years. Grain yield was higher with s1 compared with s2 in all years (Figure 1). Nitrogen application increased grain yield in 2006 and 2007 and stover yield in 2006 and 2007 with s0 (Figure 2). The effects of PP on stover and grain yield at physiological maturity were not consistent. However, stover yield was less responsive to N application in both years with coefficients of determination ranging from 0.57 to 0.99 (Figures 2A and B). The regression equations were not significant for 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. With skip-row configurations, N application resulted in higher grain yield, though increasing N rate above 50 kg N ha⁻¹ did not bring corresponding grain yield increase (Figures 2C and D). Increasing N rate resulted in a quadratic increase in grain yield with a peak at 150 kg N ha⁻¹ with s0 for the two years with R² values of 0.90 to 0.99 (Figures 2C and D).

3.4. Nitrogen concentration, uptake and use efficiency

Stover and grain N concentration at physiological maturity were not affected by the 2- and 3-way interactions of RPA, PP and N rate in

2006 and 2007 (Tables 1 and 2). The RPA x N rate interaction significantly affected grain N uptake in

2007 due to increased N uptake of 15% for s0 and 9% for s1 and s2 with N application.

Figure 2. The effect of N application and planting configuration on stover (A and B) and grain yield (C and D) at physiological maturity in south-central 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.

The RPA x PP interaction affected IE_N in 2006 and 2007 and PE_N in 2006 (Tables 1 and 2). Doubling PP with s0 and s2 increased IE_N in 2006 and 2007 by 19 and 20%, respectively (Figures 3A and B). The RPA x PP interaction affected PE_N but inconsistently over

years, and mean PE_N was higher with s0 than with skip row planting (Figures 3C and D). The N rate x RPA interaction affected FPF_N in 2006. With each RPA, increasing N rate from 50 to 100 and finally to 150 kg ha⁻¹ N resulted in 44 to 67% lower FPF_N .

Table 1. Analysis of variance summary for grain sorghum with three row planting arrangement, two plant populations and four N rates in 2006 in south-central Nebraska.

		Stover	Grain	Stover	Grain	PFP _N	AE _N	RE _N	PE _N	IE _N
		N Concentration (mg kg ⁻¹)		---N Uptake (kg ha ⁻¹)-----		-----kg kg ⁻¹ -----				
	DF	Mean Square-----								
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RPA	2	0.438**	0.594**	6867**	357.1ns	7853**	3318**	0.0262ns	5244**	298.7**
PP	1	0.763**	0.171**	3371**	841.7ns	296.4ns	1131ns	0.0043ns	15.65ns	687.4ns
N	3	0.199ns	0.035ns	2994**	432.5ns	61224**	2780**	0.0030ns	591.2ns	341.7ns
RPA x PP	2	0.092ns	0.016ns	328.2ns	101.4ns	160.8ns	98.41ns	0.0010ns	1611**	180.1*
RPA x N	6	0.172ns	0.039ns	200.9ns	687.3ns	365.1*	653.2ns	0.0313ns	124.0ns	68.08ns
N x PP	3	0.134ns	0.034ns	89.98ns	31.8ns	193.7ns	402.6ns	0.0152ns	348.7ns	35.68ns
RPA x PP x N	6	0.014ns	0.029ns	249.4ns	544.4ns	66.75ns	562.4ns	0.0076ns	96.64ns	9.97ns
Residual	46	0.095	0.030	278.0	290.8	96.46	357.8	0.0177	423.5	48.30

* = $P \leq 0.05$; ** = $P \leq 0.01$; ns = Not significant**Table 2.** Analysis of variance summary for effects of row planting arrangement (RPA), plant population (PP), and N rates on grain sorghum in 2007 in south-central Nebraska

		Stover	Grain	Stover	Grain	PFP _N	AE _N	RE _N	PE _N	IE _N
		N Concentration (mg kg ⁻¹)		---N Uptake (kg ha ⁻¹)-----		-----kg kg ⁻¹ -----				
	DF	Mean Square-----								
RPA	2	1.053**	11.35**	21565**	740.9ns	9120.1**	9030**	0.0937*	4854*	39.2ns
PP	1	2.868**	0.72*	24646**	5680**	36.56ns	91.81ns	0.0037ns	179ns	1107**
N	3	0.130ns	7.2*	2598.6*	4967**	97577**	6280**	0.0949*	3564ns	50.69ns
RPA x PP	2	0.117ns	0.08ns	558.6ns	265.1ns	81.12ns	1364ns	0.0166ns	3849ns	208.2**
RPA x N	6	0.112ns	0.05ns	178.2ns	1576.4*	124.9ns	169.9ns	0.0145ns	432.4ns	44.17ns
N x PP	3	0.028ns	0.01ns	142.7ns	59.4ns	92.28ns	962.5ns	0.0009ns	1001ns	28.54ns
RPA x PP x N	6	0.024ns	0.21ns	264.4ns	1216.4ns	416.3ns	100.9ns	0.0125ns	1073.ns	17.61ns
Residual	4	0.096	0.15	711.2	569.6	195.2	1234.1	0.0209	1433.6	36.41

* = $P \leq 0.05$; ** = $P \leq 0.01$; ns = Not significant

Compared to the zero N treatment, increased N rate resulted in increased plant N concentration in 2006 by up to 18% and increased grain N concentration in 2007 by up to 12% (Table 3). Application of N resulted in up to 30 and 22% more stover N uptake in 2006 and 2007, respectively, and up to 30% more

grain N uptake in 2007 (Table 3).

Averaged over N rates, s0 had higher PFP_N, AE_N and PE_N than s1 and s2 in 2006 and 2007 (Figures 4 A, B and C). Conventional row planting (s0) had higher IE_N and RE_N only in 2007 (Figures 4 D and E). Generally, s1 had higher or equal NUE compared with

s2 (Figure 4). Averaged over RPA, 50 kg ha⁻¹ N had higher PFP_N and AE_N than with higher N rates in both 2006 and 2007 (Figures 5 A and B). No N appli

cation and/or 50 kg ha⁻¹ N had higher REN in 2007 (Figure 5D) and higher IE_N in 2006 compared with 100 and 150 kg ha⁻¹ N (Figure 5E).

Figure 3. Effect of plant population x row planting arrangement interaction on IE_N in 2006 and 2007 (A and B), and PE_N in 2006 and 2007 (C and D) in south-central Nebraska. s0 = conventional planting with all rows planted, s1 = alternate rows planted, s2 = two rows planted alternate with two rows skipped. PP1 = 75,000 and PP2 = 150,000. Y-bars = LSD (0.05) within site-year.

Table 3. Effect of N application rates on N concentration, uptake, and use efficiency in grain sorghum in 2006 and 2007 in south-central Nebraska.

N (kg ha ⁻¹)	-----2006-----				-----2007-----			
	Stover	Grain	Stover	Grain	Stover	Grain	Stover	Grain
	N concentration(mg kg ⁻¹)	N concentration(mg kg ⁻¹)	---N uptake (kg ha ⁻¹)---	---N uptake (kg ha ⁻¹)---	--N concentration (mg kg ⁻¹)----	--N concentration (mg kg ⁻¹)----	--N uptake (kg ha ⁻¹)--	--N uptake (kg ha ⁻¹)--
0	6.25	10.65	67.5	90.2	7.41	14.36	84.9	122.3
50	6.17	13.06	76.9	100.6	7.33	15.26	97.5	147.9
100	6.45	11.53	89.8	105.7	7.68	15.81	103.5	164.5
150	6.70	13.29	96.3	121.6	7.83	16.35	109.2	174.6
P value	0.114	0.706	0.001	0.453	0.264	0.001	0.016	0.001
LSD	0.652	4.470	11.12	33.37	0.566	0.642	13.23	12.11

Figure 4. Effect of row planting arrangement on PFP_{NN} (A) AE_N (B), PE_N (C), IE_N (D) and RE_N (E) in 2006 and 2007 in south-central 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

Figure 5. Effect of N application rate (0, 50, 100 and 150 kg N ha⁻¹) on PFP_N (A), AE_N (B), PE_N (C), RE_N (D) and IE_N (E) in 2006 and 2007 in south-central Nebraska. Y-bars = LSD (0.05) within site-year

4. Discussion

According to Stone *et al.*, (1996), water deficit at half bloom stage of grain sorghum will affect grain yield more than water deficit in the vegetative or grain fill stages. The relatively high climatic deficit observed at

vegetative and half bloom stages could be attributed to low in-season precipitation and uneven distribution of rainfall events. Sorghum was planted each year when soil water was adequate to ensure good plant establishment. The stirred soil water met evaporative

demands, thus eliminating any adverse effect of soil water deficit at the half bloom stage. Moreover, moderately dry periods may not affect grain yield since sorghum is noted for its ability to withstand dry conditions (Shackel and Hall, 1984). Initial stored soil water and in-season precipitation supported high biomass production with s0 resulting in greater grain yield compared to both s1 and s2 (Abunyewa *et al.*, 2010; Abunyewa *et al.*, 2011).

The low response to higher N (above 50 kg N/ha) with the skip row configuration 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). Though Wortmann *et al.*, (2007) and Varvel and Wilhelm (2003) reported yield response of grain sorghum to increased N rate, 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 (-313 mm) at vegetative and half bloom stages.

Kamoshita *et al.*, (1998), reported that increased N application resulted in increased grain N concentration in grain sorghum. Similar observation have been made with N concentration in grassland yield and maize (Ortega *et al.*, 2016; Chen *et al.*, 2015). As N rate increased, the amount of N translocated from biomass to grain increased in both 2006 and 2007. The amount of N translocated from biomass to grain in 2006 ranged between 29% for no N application and 35% for high N application compared to 46% for no N and 51% N for high N application translocated to the grain in 2007. According to Hirel *et al.*, (2007), after flowering, the amount of N accumulated in the plant biomass is remobilized and translocated to the grain.

According to Dobermann (2005), PFP_N is the most useful component of NUE 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 components with increased N rate (Wortmann *et al.*, 2007; Buah *et al.*, 1998). Lower NUE with skip-row is related to reduced yield, likely due 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 NUE 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. Sorghum cultivar and management differences can also affect NUE (Gardner *et al.*, 1994; Sow *et al.*, 1998).

5. Conclusions

Rainfall is normally adequate in South-Central Nebraska such that s0 yields are likely to be higher than s1 and s2 yields. Grain sorghum yield, N concentration and N uptake were affected by N rates. Grain yield response to N rate for each RPA was quadratic in 2006 and 2007 with very high coefficients of determination. With each RPA, the addition of 50 kg ha⁻¹ N increased NUE but raising the rate to 100 or 150 kg ha⁻¹ N resulted in significant reduction in NUE. Addition of 150 kg ha⁻¹ N with s0 and 100 kg ha⁻¹ N with skip-row planting gave the highest grain yield to N application in both years.

Conflict of interest

The authors declare that there are no conflicts of interest.

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