Biomass and Nitrogen Use Efficiency of Grain Sorghum with Nitrogen and Supplemental Irrigation

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ABSTRACT

Poor rainfall distribution and poor soil fertility in the humid coastal plain region may affect grain crop production. Nitrogen insufficiency and water stress can both reduce crop yield, but little information is available on whether supplemental irrigation (SI) and N fertilization can alleviate both water stress and nutrient deficiency in humid regions. A field sorghum [*Sorghum bicolor* (L.) Moench] study was conducted under a variable-rate center pivot. The objective of our study was to determine the combined effects of N fertilization (0, 85, and 170 kg N ha^{-1}) and SI (0, 50, and 100% of the full irrigation rate) on aboveground biomass (AB), nitrogen uptake (NU), and nitrogen-use efficiency (NUE) of two varieties (VAR) of grain sorghum in coastal plain region of the United States. Aboveground biomass and NU varied with SI ($p \leq 0.001$) and levels of N ($p \leq 0.001$). In irrigated treatments, the rates of 85 and 170 kg N ha^{-1} resulted in significantly higher AB, NU, and NUE. Averaged across years, VAR, N and SI, grain sorghum applied with 170 kg N ha^{-1} and 100% SI had the greatest AB of 3997 kg ha^{-1}. Sorghum with 85 and 170 kg N ha^{-1} and 100% SI treatment had the greatest NUE of 60.5 and 57.1%, respectively. Our results support our hypothesis that negative impacts of water stress and nutrient deficiency could be mitigated by SI and N fertilization. Effective water use in irrigation and maintaining a sufficient amount of N will improve the AB, NU, and NUE of grain sorghum.

Core Ideas

- Effective use of water and N improved biomass and nutrient use efficiency of sorghum.
- Sorghum applied with N and 100% irrigation had the greatest biomass.
- Sorghum with 85 kg N ha^{-1} and 100% irrigation had the greatest nutrient use efficiency.

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High-yielding grain crops, such as corn (*Zea mays* L.) and sorghum [*Sorghum bicolor* (L.) Moench], require large application rates of N fertilizer to reach optimal yields (Blackmer and Voss, 1997). Widespread use of irrigation, along with use of adapted hybrids and greater use of fertilizer, has greatly increased average yields of grain sorghum in Central and semiarid Southern High Plains region of the United States (Herron et al., 1963). However, little is known about the response of grain sorghum to the combined effects of irrigation supply and N fertilization in humid Coastal Plains region of the United States. Simultaneous application of water and nutrient supply requires careful management, but offers significant potentials for improved crop yield and/or nutrient efficiency. Combining soil and water conservation measures with available nutrient inputs optimize crop production and economic benefit in cereal-based farming systems (Zougmoré et al., 2004). Our hypothesis in this study is that the negative impacts of water stress and nutrient deficiency could be mitigated by supplemental irrigation and N fertilization in sorghum production.

Grain sorghum is an important grain crop that is considered drought tolerant and suitable to be grown in regions drier than those for corn (Swick, 2011). Many producers falsely believe that cultivating sorghum requires little management because growing sorghum requires less water than some other crops and can survive drought conditions (Carter et al., 1989; Eck and Musick, 1979). Although sorghum can survive and produce grains under adverse conditions, yield can be greatly reduced by environmental stress and poor management. Exposing grain sorghum to severe moisture stress resulted in sorghum growth and development failures (Abadi et al., 2014). Eck and Musick (1979) found that the yield of sorghum was reduced by about 50% when plants were under water stressed at early boot to heading stage. This interest can be attributed to the desire of improving water use efficiency as well as complement management of other crop inputs such as N fertilization.

In more humid regions like the southeastern coastal region of the United States, corn is usually a better choice than grain sorghum, but renewed interest in grain sorghum occurs because

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Abbreviations: AB, aboveground biomass; CP1, center pivot no. 1; DAP, days after planting; GY, grain yield; NU, nitrogen uptake; NUB, nitrogen uptake of sorghum biomass; NUE, nutrient use efficiency; NUG, nitrogen uptake of sorghum grain; SI, supplemental irrigation; SWP, soil water potential; UAN, urea and ammonium nitrate; VAR, variety.

of much hotter and drier conditions as results of the recent changing climate that brought water-scarce conditions. There are two major approaches to improving and sustaining productivity under water-scarce conditions, namely: (i) modifying plants to suit the environment through genetic improvements; and (ii) modifying the soil environment by providing irrigation and reducing water loss. Variable-rate irrigation systems used for site-specific irrigation are capable of spatially allocating limited water resources while potentially increasing profits for producers (Sigua et al., 2017; Stone et al., 2015, 2016; Stenger et al., 2002; Ilsemann et al., 2001). Future climate change could have the potential to significantly alter the conditions for crop production, with important implications of irrigation management for worldwide food security (El Afandi et al., 2010; Rosenzweig and Hillel, 1998).

Irrigation in the humid coastal plain region of the United States has increased rapidly during the past few years because of poor rainfall distribution and soil conditions such as high soil compaction, low water holding capacity, and poor soil fertility that often limit production of grain crops like corn and grain sorghum (Sigua et al., 2016, 2017; Stone et al., 2015, 2016; Camp et al., 1998). If compacted soils are not disrupted by deep tillage, plant rooting is limited to shallow soil depths. Crops may suffer from drought stress after 5 to 7 d without rainfall unless irrigation is provided (Lambert, 1980). In an attempt to improve crop production, some farmers have started using irrigation scheduling based on soil moisture and calculations of crop evapotranspiration commonly performed by means of an energy balance method (Rode et al., 2009; Gooday et al., 2008; Rivett et al., 2008; Donatelli et al., 2006; Allen et al., 1998).

With poor rainfall distribution in humid coastal plain region of the United States, there are increasing concerns with respect to the availability of water resources, as well as the impact of farming practices on the environment, such as nitrate leaching due to excessive application of N (Sigua et al., 2017; Keikha and Keikha, 2013; Gheysari et al., 2009). Hence, it is helpful to develop sound technologies for resource management that maximize the efficient use of water and N to achieve sustainable agricultural production (Zougmoré et al., 2004). Only limited data are available on irrigating grain sorghum in humid regions. The objective of this study was to determine the effects of N fertilization (0, 85, and 170 kg N ha^{-1}) with SI (0, 50, and 100% of the full irrigation rate) on aboveground biomass (AB), nitrogen uptake (NU) and nitrogen-use efficiency (NUE) of two varieties (VAR) of grain sorghum in the coastal plain region of the United States.

MATERIALS AND METHODS

Site Description

From 2013 to 2014, a grain sorghum study was conducted under a variable-rate center pivot 1 (CP1) at the Coastal Plains Research Center near Florence, SC. The study site (34°14′38.3″–34°14′40.3″ N; 79°48′29.0″–79°48′35.5″ W) has a long-term historical data set on soil physical and chemical properties because of different types of research conducted since 1990 (Karlen et al., 1990). Each year, field preparation started with applications of glyphosate (N-(phosphonomethyl)glycine) and Roundup Weathermax (N-(phosphonomethyl)glycine) to control winter weeds. Two days after emergence of grain sorghum, Clarity (diglycolamine salt of 3,6-dichloro-Q-anisic acid) (1.12 kg a.i. ha^{-1}) and atrazine (6-chloro-N2-ethyl-1,3,5-triazine-2,4-diamine) (2.8 kg a.i. ha^{-1}) were also applied in the field for weed control in 2013 and 2014, respectively. Field tillage during sorghum planting consisted of in-row sub-soiling. Two varieties of sorghum (Dekalb A571 and Pioneer 84P80) were planted according to a planting distance of 10 cm between plants and 75 cm between rows, with a planting population of about 272,277 seeds ha^{-1}. The planting and harvest dates of sorghum for 2013 and 2014 were 10 July 2013 and 18 July 2014 and 10 Oct. 2013 and 18 Sept. 2014, respectively. The soil type at the study site: CP1 is a Norfolk loamy sand (fine loamy, kaolinitic, thermic Typic Kandiudults). Selected physical and chemical properties of the Norfolk soil in the study site are presented in Table 1. Each main experimental plot was about 13 m wide and about 27 m long.

Experimental Treatments and Experimental Design

Experimental design was a randomized complete block in split-split plot arrangement. Experimental treatments were consisted of three levels of SI, three levels of N application and two VAR of sorghum with four replications. Main plots (27 × 13 m) were the supplemental irrigation (SI) levels (0, 50, and 100% of full irrigation rate), subplots (9 × 13 m) were the levels of N (0, 85, and 170 kg N ha^{-1}) and sub-sub plots (4.5 × 13 m) were the sorghum VAR (Pioneer and Dekalb).

Fertilizer Application Treatments

All N fertilizer was applied via fertigation through the center-pivot system annually in two split applications. The first N application was to all plots at the rate of 85 kg N ha^{-1}. A second N application was applied at this rate to only the high N plots. Nitrogen was applied using the center-pivot irrigation system and injecting urea and ammonium nitrate (UAN) 30% into the incoming water stream at the base of the J tube. The pump injection rate was controlled by varying the pump speed using a 0 to 5 voltage direct current (VDC) signal to the pump controller. The onboard computer controlling the variable-rate center-pivot system calculated the desired injection rate and the proper control voltage setting, and then set the appropriate control voltage for the pump controller. Nitrogen applications were applied with the minimal water application depths to minimize irrigation water applications to non-irrigated plots. For this experiment, all N was delivered with 1.8-mm irrigation depth operating at 100% duty cycle. At the end of the N application, the system was again run in non-plot area to purge the system of N. Phosphorus and K were uniformly applied in granular form across all plots each spring based on soil testing and recommendations of the Clemson University Extension Agricultural Service Laboratory. Phosphorus and K fertilizers were also applied to all subplots at the rate of 34 and 28 kg P_2O_5 ha^{-1} and 90 and 67 kg K_2O ha^{-1} in 2013 and 2014, respectively. Supplemental irrigation treatment is described below.

Supplemental Irrigation Treatment

The SI treatments consisted of non irrigated (0%), limited irrigation (50%), and full irrigation (100%) rates that were based on using soil water potential sensors to maintain soil water potentials below -30 kPa (equivalent to 50 or 0% SI) and/or above

Table 1. Selected properties of the Norfolk soil in the study area.

Soil properties	Soil depth, cm	
	0–15	15–30
Physical properties		
Sand, g kg^{-1}	807	–
Silt, g kg^{-1}	167	–
Clay, g kg^{-1}	26	–
Texture	Loamy sand	–
Chemical properties		
pH	5.71	5.96
EC, dS m^{-1}	0.25	0.14
TN, %	0.098	0.051
TC, %	1.278	0.741
TIN, $NO_2 + NO_3$–N, mg kg^{-1}	19.11	11.12
PO_4–P, mg kg^{-1}	6.67	3.18
Al, mg kg^{-1}	1236.2	1354.5
Ca, mg kg^{-1}	527.5	398.7
Fe, mg kg^{-1}	22.5	22.2
K, mg kg^{-1}	101.2	54.5
Mg, mg kg^{-1}	82.3	48.1
Mn, mg kg^{-1}	13.4	9.2
Na, mg kg^{-1}	41.9	41.6
P, mg kg^{-1}	51.4	38.6
Zn, mg kg^{-1}	3.9	2.3
Mineralogy	Kaolinite, chlorite, quartz	

-30 kPa (equivalent to about 100% SI) in the surface 30 cm of soils. The optimal irrigation was set to maintain soil water potentials above -30 kPa. The 2013 and 2014 30-cm soil water potentials for the 0, 50, and 100% irrigation treatments are shown in Fig. 1. Plots were instrumented with tensiometers at depths of 30 and 60 cm. The Norfolk loamy sand in our study site has a water holding capacity of approximately 24.3 mm in the surface 0.30 m (Peele et al., 1970). A soil water potential (SWP) value of -30 kPa represents an approximately 50% depletion of the plant-available water holding capacity. A 12.5-mm irrigation was initiated when SWP at the 0.30-m depth was below -30 kPa in the 100% irrigation plot with high N. Soil water potentials were measured in all irrigation treatments for the high N rate using tensiometers at two depths (0.30 and 0.60 m). Measurements were recorded at least two times each week. The other irrigation treatments (0, 50, and 100%) received an application proportional to the 100% 12.5-mm application. The seasonal evapotranspiration for the sorghum crop was found by calculating the daily reference evapotranspiration from an adjacent weather station using the ASCE standard for grass (Walter et al., 2000) and the dual-crop-coefficient method of Allen et al. (1998).

Figure 2 shows the monthly average of precipitation and amount of irrigation applied to each subplot in 2013 and 2014. At 100% SI, the total amount of irrigation water applied in 2013 and 2014 were 38.1 and 12.9 mm, respectively. The total amount of irrigation water applied in 2013 and 2014 in plots with 50% SI were 19.05 and 6.35 mm, respectively (Fig. 2). Supplemental irrigation was delivered via the center pivot irrigation system that was modified to permit variable application depths (Omary et al., 1996). The center pivot length (137 m) was divided into 13 segments, each 9.1 m in length. The 9.1-m segment is related to the center pivot length of 137 m with 13 segments, so each segment is about 10.5 m. There is about 1.4 m on each end of the plot to account for the edge effect.

Variable rate water applications were accomplished by using three manifolds in each segment; each had nozzles sized to deliver 1×, 2×, or 4× of a base application depth at that location along the center pivot length. All combinations of the three manifolds provided application depths of 0 through 7× of the base rate, and the 7× depth was 12.7 mm when the outer tower operated at 50% duty cycle. A more detailed description of the water delivery may be found in Stone et al. (2015) and Omary et al. (1996).

Sorghum Aboveground Biomass

Aboveground biomass of grain sorghum was determined from 10 randomly selected plant samples taken from the center of each subplot (9 × 13 m) over the three stages of growth for sorghum, namely 30 days after planting (DAP), 60 DAP, and at grain maturity (90 DAP), respectively. Plants were harvested by cutting the aboveground biomass from the surface of the soil. Aboveground biomass was oven-dried at 60°C for about 96 h.

Nitrogen Tissue Analysis, Nitrogen Uptake, and Nitrogen-Use Efficiency

Aboveground biomass and grain of sorghum at grain maturity (90 DAP) were ground to pass through a 1-mm mesh screen in a Wiley mill. Ground biomass and grain samples ($n = 63$) were analyzed for total N using the Elementar CNS analyzer. Nitrogen uptake based on AB and based on grain yield (GY) was calculated using Eq. [1] and [2] below.

$$\mathrm{NUB} = \mathrm{CTN_b} \times \mathrm{AB} \qquad [1]$$

$$\mathrm{NUG} = \mathrm{CTN_g} \times \mathrm{GY} \qquad [2]$$

where NUB and NUG = nitrogen uptake (kg ha^{-1}) of biomass (aboveground) and grain (grain yield), respectively; CTN_b and CTN_g = concentration of N (%) in biomass and grain, respectively; and AB and GY = aboveground biomass (kg ha^{-1}) and grain yield (kg ha^{-1}), respectively.

Nitrogen use efficiency was computed by combining the NU of grain sorghum based on AB + GY. Nitrogen-use efficiency of grain sorghum in our study as shown in Eq. [3] was calculated following the method described by Raun and Johnson (1999).

$$\mathrm{NUE} = [(\mathrm{NF} - \mathrm{NC})/R] \times 100 \qquad [3]$$

where NUE = nitrogen use efficiency (%), NF = total sorghum N uptake (biomass + grain; kg ha^{-1}) from fertilized plots, NC = total sorghum N uptake (biomass + grain; kg ha^{-1}) from unfertilized plots, and R = rate of fertilizer N applied (kg N ha^{-1}).

Data Reduction and Statistical Analysis

Data (aboveground biomass and N uptake) were analyzed with a four-way ANOVA using the SAS PROC MIXED model (SAS Institute, 2000). The model included four sources of variations: (i) year effect (Y); (ii) supplemental irrigation (SI); (iii) nitrogen (N); and (iv) variety (VAR). For this study, *F* tests indicated significant ($p \leq 0.0001$) results, so means of Y, SI, N, and VAR were

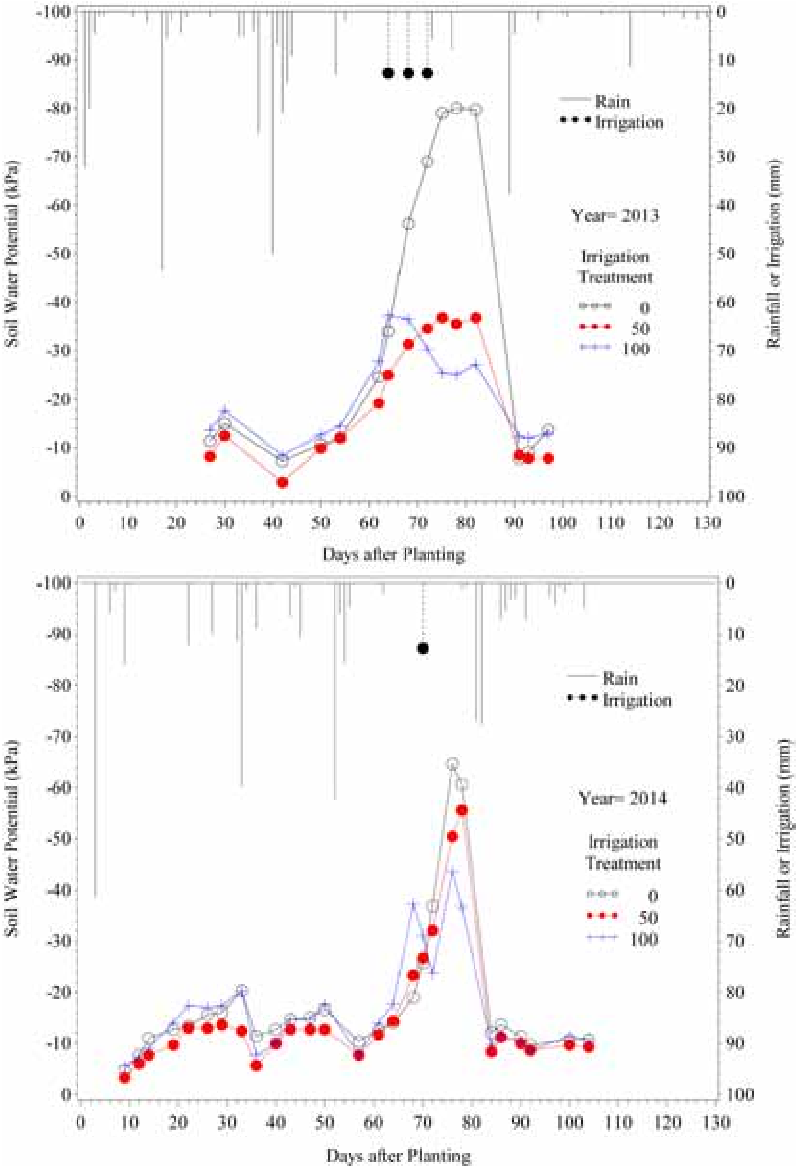

Fig. 1. The 2013 and 2014 30-cm soil water potentials for the 0, 50, and 100% irrigation treatments.

separated following the least significance difference (LSD) test using appropriate error mean squares (SAS Institute, 2000).

RESULTS AND DISCUSSION

Effect on Aboveground Biomass Yield

Interaction of N fertilization and SI significantly ($p \leq 0.01$) increased AB of grain sorghum. Aboveground biomass varied significantly with the different levels of SI ($p \leq 0.001$), N fertilization ($p \leq 0.01$), but not with sorghum VAR (Table 2). The average AB of Dekalb variety of about 3521.4 kg ha^{-1} was not significantly different from the average AB of Pioneer variety (3593.9 kg ha^{-1}). Among the plots with N treatments, the greatest AB of grain sorghum was from plants treated with 170 kg N ha^{-1} (3739.3 kg ha^{-1}) followed by 85 kg N ha^{-1} (3644.1 kg ha^{-1}). The least amount of AB was from plots with 0 kg N ha^{-1} (2891.9 kg ha^{-1}). Growth of sorghum under N deficient (0 kg N ha^{-1}) conditions implies a slower rate of accumulation of dry matter. Both leaves and stems may die as a result of stress due to N deficiency. Dying of tissue is a function of the N status of the vegetation. It begins when the N content drops below the threshold value for unrestricted growth, the relative rate gradually increasing until a final value of 0.3 d^{-1} (Van Kuelen, 1981). Results of our study were similar to earlier studies of Muchow (1988) and Lugg and Sinclair (1981). Several studies indicate that a threshold N concentration is required for leaf expansion (Muchow, 1988; Lugg and Sinclair, 1981) and that this N threshold may be greater for leaf tissues than for other tissue types (Wilson and Brown, 1983). Lafitte and Loomis (1988) described the effect of N stress on biomass yield that involved decreased leaf development and duration and reduced radiation interception relative to the well-fertilized treatments.

Of the irrigation treatment shown in Table 2, the greatest AB was from plots with 100% SI (3892.4 kg ha^{-1}), whereas the least amount of AB (3015.8 kg ha^{-1}) was from plots with 0% SI. Results of our biomass study were similar to previous studies on grain sorghum such as those conducted in the Texas High Plains under either full irrigation or limited irrigation (Hao et al., 2014; Bean et al., 2013; Maughan et al., 2012; Tamang et al., 2011; Propheter et al., 2010). Hao et al. (2014) reported that biomass yield of grain sorghum when averaged across years and cultivars

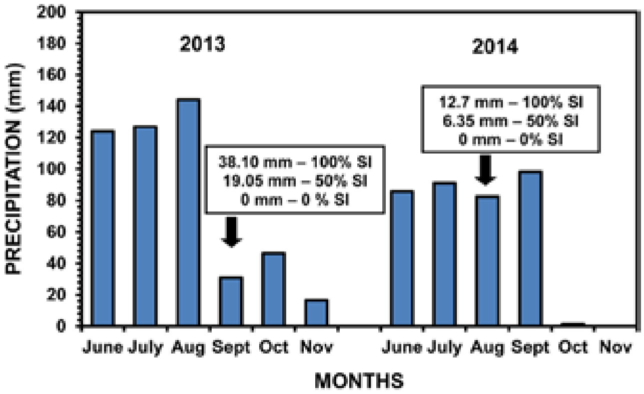

Fig. 2. Average monthly rainfall distribution in the study site during the growing season of sorghum (2013–2014). Irrigation amounts applied to respective plots is represented by the numbers with box enclosures.

increased from no irrigation to full irrigation. Biomass yield of sorghum under full and limited irrigation treatment were 87 and 41% in 2009 and 87 and 62% in 2010. These biomass yields were significantly higher than that of non-irrigated plots in 2009 and 2010, respectively. A study in China showed that sorghum biomass of the full irrigation treatment was 56% greater than that of the rainfed control (Li et al., 2005). Farré and Faci (2006) reported that biomass yield of sorghum with moderate and full irrigation treatments increased by 39 to 252% as compared with severe water deficit treatment in a Mediterranean environment. Deficit irrigation reduces crop growth and yield because it reduces biomass and the harvest index significantly (Stone et al., 2001; Bryant et al., 1992).

In our study, the growing season rainfall totals for each year were lower than the long-term average total of approximately 430 mm. In each year, the rainfall totals exceeded the calculated crop evapotranspiration (Fig. 1). In both 2013 and 2014, rainfall was generally adequate to maintain adequate SWP values except during the midpoint of the season from approximately 60 to 70 DAP (stage 6, mid-bloom to stage 7, soft dough). During this time, three irrigations in 2013 and one irrigation in 2014 were needed to maintain the SWP values above -30 kPa.

On our irrigated plots with 100% SI, sorghum plants that were fertilized with 170 kg N ha^{-1} had the greatest AB (3997 kg ha^{-1}). These results suggest that effective use of water in irrigation and maintaining sufficient amount of N can improve the biomass productivity of grain sorghum (Fig. 3). Integrated effect of N fertilization and irrigation scheduling may improve biomass and grain yield of most cereal crops (Hossain et al., 1996; Turk and Tawaha, 2002; Yousaf et al., 2014). Our results have shown higher biomass in the plots with N fertilization (Fig. 3). Increased concentration of available N can enhance root density directly by stimulation of growth near N-rich zones (Officer et al., 2009) and indirectly through crop vigor (Palta et al., 2011). According to Vetterlein and Marschner (1994), an important relationship between nutrient supply and soil water balance is the increase in plant shoot sizes due to improved nutritional status and thereby, the increase in water requirement of the crop. This may be due to the interaction between adequate water use and better nutrient availability. Other studies have shown that a high correlation between the dry matter production in sorghum and the application of different levels of N fertilizers (Abadi et al., 2014; Sweeney and Lamm, 1993; Mascagni and Sabbe, 1990; Locke and Hons, 1988; Roy and Wright, 1974), whereas water deficit in sorghum during vegetative growth stage decreased the total weight of plant shoots (Abadi et al., 2014). Limited but timely irrigation application can be used to avoid critical stress and frequently increase crop yield (Sweeney and Lamm, 1993; Hiler and Howell, 1983). Similar results were reported by Stone et al. (2012) from their work on irrigation and N impact on bermudagrass [*Cynodon dactylon* (L.) Pers.] yield. They concluded that timely supplemental irrigation to maintain soil water potentials above -30 kPa can increase bermudagrass yields in the southeastern Coastal Plain region.

Table 2. Aboveground biomass (kg ha^{-1}) of grain sorghum as affected by supplemental irrigation and N fertilization in 2013 and 2014 cropping.

Treatments	2013 Cropping	2014 Cropping	Average
Irrigation (SI)			
0%	2951.6 ± 1525	3152.2 ± 1643	3051.8 ± 1584b†
50%	2926.2 ± 1510	3668.1 ± 1430	3297.2 ± 1470b
100%	3320.3 ± 1747	4655.1 ± 1928	3892.4 ± 1838a
LSD(0.05)			300.2
Nitrogen (N)			
0 kg N ha^{-1}	2784.1 ± 1563	2999.8 ± 1590	2891.9 ± 1576b
85 kg N ha^{-1}	3160.9 ± 1465	4288.3 ± 2657	3644.1 ± 2061a
170 kg N ha^{-1}	3253.1 ± 1744	4387.5 ± 2817	3739.3 ± 2280a
LSD(0.05)			300.2
Variety (VAR)			
Dekalb	3098.0 ± 1519	4368.3 ± 1803	3521.4 ± 1661a
Pioneer	3034.1 ± 1677	4153.6 ± 1611	3593.9 ± 1639a
LSD(0.05)			2476.6
Sources of variations			Level of significance
Year (Y)			‡
Irrigation (SI)			***
Nitrogen (N)			**
SI × N			**

** $p \le 0.01$.

*** $p \le 0.001$.

† Means followed by the same letter(s) under each column and subheading are not significantly different from each other at $p \le 0.05$.

‡ $p \le 0.0001$

Biomass productivity of grain sorghum as shown in our results was significantly affected by the interactions of N and SI. Similar results were reported by Hao et al. (2014) from their study in Texas. They found that under full irrigation, grain sorghum can obtain high biomass yield with an optimum N rate of 148 to 183 kg N ha^{-1} in 2 yr. Interactions between N and SI can influence several processes from ecosystem to molecular levels. The least amount of AB in our study was from the non-irrigated plots with 0 kg N (Fig. 3). Nitrogen and water deficit can reduce plant growth, primarily due to a reduction of the stomatal conductance that inhibits the carbon assimilation (Bradford and Hsiao, 1982). The first process affected by water deficit is foliar development and expansion (Bradford and Hsiao, 1982). Nitrogen demand is also drastically reduced in early water deficits (Bradford and Hsiao, 1982). Both N and water deficiency can affect leaf expansion and leaf photosynthesis simultaneously (Jeuffroy et al., 2002; Durand et al., 1995; Gastal and Saugier, 1989). In the longer term, water deficit may further induce N deficiency that may limit photosynthesis (Arora et al., 2001; Ciompi et al., 1996;

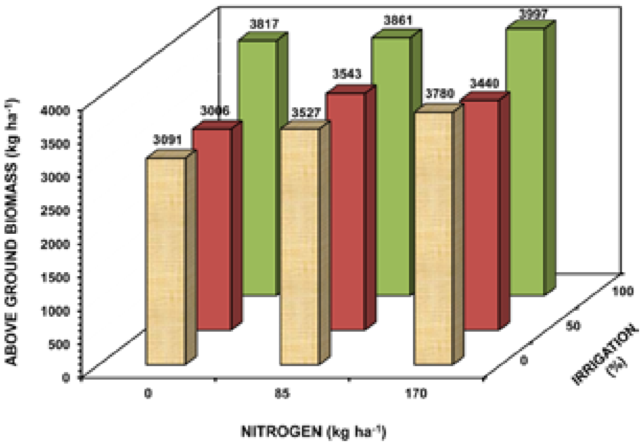

Fig. 3. Average aboveground biomass of sorghum as affected by N fertilization and supplemental irrigation (2013–2014).

Table 3. Nitrogen uptake (kg ha^{-1}) of grain sorghum biomass as affected by supplemental irrigation and N fertilization in 2013 and 2014 cropping.

Treatments	2013 Cropping	2014 Cropping	Average
Irrigation (SI)			
0%	44.7 ± 24	68.3 ± 34	56.5 ± 34b†
50%	43.5 ± 23	63.6 ± 36	53.6 ± 29b
100%	49.6 ± 24	86.1 ± 51	67.9 ± 37a
LSD(0.05)			5.7
Nitrogen (N)			
0 kg N ha^{-1}	31.9 ± 16	59.6 ± 39	45.8 ± 28c
85 kg N ha^{-1}	48.4 ± 22	73.9 ± 39	61.2 ± 31b
c70 kg N ha^{-1}	57.5 ± 25	84.5 ± 51	71.0 ± 38a
LSD(0.05)			5.7
Variety (VAR)			
Dekalb	48.1 ± 26	72.5 ± 45	60.3 ± 35a
Pioneer	43.7 ± 21	72.8 ± 44	58.2 ± 33a
LSD(0.05)			5.7
Sources of variations			Level of significance
Year (Y)			‡
Irrigation (I)			***
Nitrogen (N)			‡
Variety (VAR)			ns
N × VAR			**

** $p \le 0.01$.

*** $p \le 0.001$.

† Means followed by the same letter(s) under each column and subheading are not significantly different from each other at $p \le 0.05$. ns, not significant.

‡ $p \le 0.0001$.

Lawlor et al., 1987; Morgan, 1984). Photosynthetic rate is largely determined by the presence of RuBP carboxylase and chlorophyll content, both linearly related to leaf N content (Evans, 1989). Moreover, the lowest amount of AB that we observed from plots with 0% SI and 0 kg N ha^{-1} is well supported by Broadley et al. (2001), who demonstrated that soil N deficiency increased the sensitivity of stomata to water deficit, inducing lower leaf water potentials in a high transpiration regime, such as in the humid coastal region where our study was conducted. Our results were also similar to the findings of other studies (Jacob et al., 1995; Onillon et al., 1995; Radin and Parker 1979).

Sadras et al. (2016) claimed that water–N interactions modulate the geochemical cycling of N, shape functional diversity of plants, can affect crop yield, grain size, root demography, leaf stoichiometry, and photosynthesis. Sinclair and Rufty (2012) suggested that management practices that increased the availability of N and water have the major drivers of gain in crop yield. Gonzalez-Dugo et al. (2010) claimed that among the environmental factors that can be modified by farmers, water and N are the main ones controlling plant growth.

Effect on Nitrogen Uptake and Nitrogen-Use Efficiency

Nitrogen uptake of sorghum biomass and NUG were both significantly affected by SI ($p \le 0.001$) and N fertilization ($p \le 0.0001$). However, NUB and NUG between sorghum varieties (Dekalb and Pioneer) were not significantly different from each other as shown in Table 3 and Table 4, respectively. Sorghum in plots with 100% SI had the greatest NUB of 67.9 kg ha^{-1} (Table 3) and NUG of 52.8 kg ha^{-1} (Table 4). Both NUB and NUG in plots that received 50 and 0% SI were statistically comparable to each other (Tables 3 and 4). As might be expected, the greatest NUB and NUG were observed from plots that were fertilized with 170 kg N ha^{-1}. On the other hand, the least amount of NUB and NUG were from plots without N fertilization (Tables 3 and 4). Our results were similar to the early results reported by Roy and Wright (1974). They found that application of 60 kg N ha^{-1} significantly increased the N uptake of the whole sorghum plants (stem + leaf + head) by 60.9% over the control. An increase of about 19% was observed with the application of 120 kg N ha^{-1}. Sorghum has continued to absorb N from the soil throughout the growing season, suggesting that accumulation of N proceeded almost linearly until maturity (Roy and Wright, 1974; Herron et al., 1963). The effectiveness with which N is used by non-legume crop plants has become increasingly important because of increased costs of manufacturing N fertilizer.

As shown by the results of our study and other studies (Moll et al., 1982; Pollmer et al., 1979; Moll and Kamprath, 1977), differences in N utilization and N use efficiency have been demonstrated, not only in differential response to N fertilizer of sorghum with or without SI, but also differences in absorption and in the utilization of absorbed N. Nitrogen uptake clearly depends on two critical processes, namely (i) water flows from the soil to the root systems, and (ii) ion diffusion fluxes in the rhizosphere. In our study, we could have had three basic methods in which nutrients make contact with the root surface for sorghum uptake. They are root interception, mass flow, and diffusion. Root interception occurs when a nutrient comes into physical contact with the root surface. The occurrence of root interception increases as the root surface area and mass increases, thus enabling the plant to explore a greater amount of soil. Mass flow occurs when nutrients are transported to the surface of roots by the movement of water in the soil (i.e., percolation, transpiration, or evapotranspiration). As in the case of the soils (Typic Kandiudults) in our study site having low fertility and low water holding capacity (Table 1), water flow is weak and/or solution concentration is low; therefore, diffusion increases in relation to mass flow (Williams and Yanai, 1996; Passioura, 1963).

Averaged across VAR and SI, the NUE of sorghum from plots fertilized with 85 kg N ha^{-1} was about 40.8% compared with the NUE of 35.8% from plots that were fertilized with 170 kg N

Table 4. Nitrogen uptake (kg ha^{-1}) of sorghum grain as affected by supplemental irrigation and N fertilization in 2013 and 2014 cropping.

Treatments	2013 Cropping	2014 Cropping	Average
Irrigation (SI)			
0%	37.7 ± 17	35.3 ± 13	36.5 ± 15b†
50%	41.8 ± 23	30.5 ± 13	36.2 ± 18b
100%	50.8 ± 24	54.7 ± 16	52.8 ± 19a
LSD(0.05)			9.8
Nitrogen (N)			
0 kg N ha^{-1}	26.9 ± 11	27.9 ± 14	27.4 ± 12b
85 kg N ha^{-1}	42.9 ± 20	42.4 ± 18	42.6 ± 19a
170 kg N ha^{-}	60.5 ± 18	50.2 ± 12	55.4 ± 15a
LSD(0.05)			9.8
Variety (VAR)			
Dekalb	43.8 ± 25	44.8 ± 28	44.3 ± 26a
Pioneer	43.0 ± 17	37.8 ± 14	40.4 ± 16a
LSD(0.05)			8.1
Sources of variation			Level of significance
Year (Y)			ns
Irrigation (SI)			***
Nitrogen (N)			‡
Variety (VAR)			ns

*** $p \leq 0.001$.

† Means followed by the same letter(s) under each column and sub-heading are not significantly different from each other at $p \leq 0.05$. ns, not significant.

‡ $p \leq 0.0001$.

ha^{-1} (Fig. 4). Sorghum with 85 and 170 kg N ha^{-1}, and 100% SI treatment had the greatest NUE of 60.5 and 57.1%, respectively (Fig. 4). Overall, the estimated increase in NUE between the 0 and 100% SI of about 79% from plots with 85 kg N ha^{-1} and 126% increase of NUE from plots with 100 kg N ha^{-1} (Fig. 3). Nitrogen absorption as shown by our results was reduced under dry soil conditions, even when mineral N is present in the soil. Our results were supported by other researchers (Gonzalez-Dugo et al., 2005; Garwood and Williams, 1967) who reported that absorption of N by roots requires the presence of water in the soil, as it is the agent that transports solutes to the soil–root interface. Moisture shortage with equal availability of N may lead to reduce uptake of N. Where N is unavailable and less sufficient moisture is available for transport, the concentration of N in the tissue drops to a much lower value. These results illustrate that moisture shortage to the plants may have both direct and indirect effects on N uptake (Van Kuelen, 1981).

SUMMARY AND CONCLUSION

Grain sorghum was grown in 2013 and 2014 to determine the combined effects of N fertilization and supplemental irrigation on aboveground biomass, N uptake, and N use efficiency. Aboveground biomass and NU varied with SI and levels of N. In irrigated treatments, the rates of 85 and 170 kg N ha^{-1} resulted in significantly higher AB, NU, and NUE. Averaged across years, VAR, N, and SI, grain sorghum applied with 170 kg N ha^{-1} and 100% SI had the greatest AB. We demonstrated that our results support our hypothesis that the negative impacts of water stress and nutrient deficiency could be mitigated by supplemental irrigation and N fertilization. An important relationship between nutrient supply and soil water balance is the increase in AB and NUE of grain sorghum due to the interaction between adequate water use and better nutrient availability. Based on our broad results, we can conclude that effective use of water in irrigation and maintaining a sufficient amount of N will improve the biomass, N uptake, and N use efficiency of grain sorghum in humid coastal plain region of the United States.

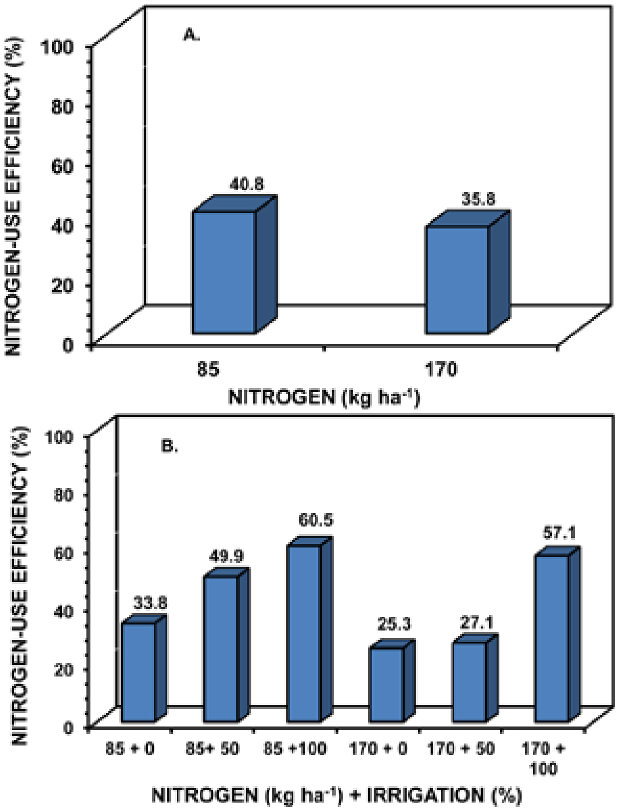

Fig. 4. Nitrogen use efficiency of sorghum with N fertilization (A) and N use efficiency of sorghum with N fertilization with supplemental irrigation (B).

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