SUPPLEMENTAL IRRIGATION FOR GRAIN SORGHUM PRODUCTION IN THE U.S. EASTERN COASTAL PLAIN

K. C. Stone, G. C. Sigua, P. J. Bauer

ABSTRACT. *Grain sorghum is one of the top five cereal crops and an important grain crop throughout the world. It is generally considered more drought tolerant compared to other grain crops such as maize. Recently, in the U.S. eastern Coastal Plain region, there was an emphasis on increasing regional grain production in which grain sorghum played an important role. The region's soils have low water holding capacities that combined with high rainfall variability cause crops frequently to be exposed to water stress. In this research, an experiment was conducted to evaluate the yield response of two grain sorghum varieties at different supplemental irrigation depths and three nitrogen levels. During our 3-year study, seasonal rainfall was adequate to produce acceptable grain sorghum yields. Seasonal rainfall ranged from 421, 365, and 357 mm in 2012, 2013, and 2014, respectively. These rainfall amounts were greater than the seasonal calculated crop evapotranspiration requirement, but rainfall distribution was not adequate to maintain acceptable soil water potentials throughout the growing season. Supplemental irrigation was 51, 38, and 13 mm in 2012, 2013, and 2014, respectively, to maintain soil water potential above -30 kPa. These irrigation amounts did not increase grain sorghum yields. No significant differences were found in grain yield between the two sorghum varieties or for increasing nitrogen applications. This lack of response to nitrogen applications may have been related to adequate supplies in the soil from previous crops. Results from this study suggest that there would be little benefit for supplemental irrigation for sorghum production in the U.S. eastern Coastal Plain.*

Keyword. *Grain sorghum, Irrigation, Irrigation management.*

Grain sorghum (*Sorghum bicolor* L.) is an important grain crop that is considered drought tolerant and suitable to be grown in regions drier than those for corn (Swick, 2011). In some areas of the country with low rainfall such as the Southern High Plains, sorghum has to some extent replaced corn (Bordovsky and Lyle, 1996). In many of these areas, irrigation is used to supplement rainfall in grain sorghum fields. In 2013, the average irrigation water applied to grain sorghum was approximately 1100 mm in Arizona, 365 mm in Texas, and 60 mm in North Carolina (USDA-NASS 2017, Quick Stats). In 2012, the U.S. Census of Agriculture reported grain sorghum production at approximately 2.1 million ha with 0.25 million ha irrigated (~12%). In much of the Southern High Plains, grain sorghum is deficit irrigated at rates below that of a well-watered crop. In western Kansas, Klocke et al. (2012) studied the impact of deficit irrigation on grain sorghum yields. In their study, grain sorghum yields increased linearly with increased irrigation amounts. Similarly, in northern Texas, O'Shaughnessy et al. (2012) reported on deficit irrigation levels in grain sorghum using automatic and manual irrigation scheduling. They found that optimum deficit irrigated yields and water use efficiencies were obtained when irrigation was from 55% to 80% of well-watered crop evapotranspiration rates.

Only limited data are available on irrigating grain sorghum in humid regions. Recently in Mississippi, Bruns (2015) found no significant impact of irrigation on sorghum grain yield and concluded that supplemental irrigation would not be necessary in the mid-south under normal seasonal conditions.

Grain sorghum yields are also influenced by fertilization. Hibberd and Hall (1990) studied the response of grain sorghum hybrids to nitrogen fertilizer. In a 3-year furrow irrigation study, they reported significant increases in sorghum grain yields by increasing nitrogen applications. In 2 of the 3 years, they observed differences among the evaluated hybrids. They determined the optimum rate of nitrogen application to be approximately 120 to 180 kg N ha^{-1}. They also observed a leveling off of grain yields at higher nitrogen concentrations. Assefa and Staggenborg (2010) investigated the impact of grain sorghum yield and hybrid advancement from 1957 through 2008. In the 52 years of data analyzed, they found hybrid yields increasing nearly 50 kg ha^{-1} per year in dryland sites with nitrogen fertilizer explaining 34% of the yield increases while the remaining yield increase was due to improved hybrids. However, irrigated grain sorghum yields remained unchanged over the same time period. They concluded that hybrid improvement programs had selected

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hybrids with better drought tolerance characteristics for dryland rather than for irrigated production.

The normalized difference vegetative index (NDVI) was developed to quantify living biomass and is the most widely recognized vegetation index (Hatfield et al., 2008). Researchers have used NDVI as a remote sensing method to characterize crop nitrogen status and make nitrogen fertilization recommendations (Raun et al., 2002; Thompson, et al., 2015; Holland and Schepers, 2010). The NDVI measurements have also been used to estimate grain yields from in-season measurements (Thompson et al., 2015). In grain sorghum, Moges et al. (2007) used NDVI measurements to determine the in-season crop status and to estimate grain yields. Their NDVI measurements from growth stage 3 were correlated with final grain yields.

In 2012, Murphy-Brown, Inc. (a division of Smithfield Grain, Rose Hill, N.C.) initiated a grain sorghum production program in the Carolinas and Virginia to increase local grain supplies for the swine industry (Murphy-Brown, 2012). Even though grain sorghum is generally drought tolerant, supplemental irrigation during drought conditions could impact grain sorghum yield potentials because the agricultural soils of the U.S. southeastern Coastal Plain Region are generally coarse-textured with low water holding capacities (Camp and Sadler, 2002). Additionally, rainfall during the growing season can be highly variable. Sheridan et al. (1979) documented that there was a 50% chance of a 20-day drought during the annual growing season in the southeastern Coastal Plain. In this research, our objective was to evaluate the yield response of two grain sorghum varieties at different supplemental irrigation depths and three nitrogen levels. Results from this study will provide the regions sorghum growers information to make informed irrigation management decisions.

MATERIALS AND METHODS

FIELD EXPERIMENT

A sorghum experiment was conducted from 2012 through 2014 under a 6-ha variable-rate center-pivot irrigation system on a Norfolk loamy sand (Typic Kandiudult) near Florence, South Carolina (34°14’36.94” N, 79 48’34.14” W, elevation 42 m). The site is located in the humid U.S. eastern Coastal Plain region and has an annual mean rainfall of 1089 mm and mean temperature of 18°C. In 2012, there were four irrigation treatments (0%, 33%, 66%, and 100% irrigation) and two nitrogen fertilization treatments (85 and 170 kg N ha^{-1}) with one cultivar (Dekalb A571) (fig. 1a). In 2013 and 2014, there were three irrigation treatments [(0%, 50%, and 100% irrigation), three nitrogen fertilization treatments (0, 85, and 170 kg N ha^{-1}), and two varieties (Dekalb A571 and Pioneer 84P80, both mid- to late-maturity varieties, i.e. greater than 70 days to mid-bloom)] (fig. 1b). In all years there were four replications. Grain sorghum was planted at the rate of 272,000 seeds/ha. The planting dates for each year are shown in table 1.

The Norfolk loamy sand has a water holding capacity of approximately 24.3 mm in the surface 0.30 m (Peele et al., 1970) (field capacity 8%, 12 kPa; wilting point 2.3%, 1500 kPa; sand/silt/clay 86%,10%, 4%; bulk density 1.3 g/cm^3). A soil water potential (SWP) value of -30 kPa corresponds to 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. Irrigations were applied on the following dates: 20 and 27 July 2012; 2 and 6 August 2012; 12, 16, and 20 September 2013; and 27 August 2014. 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%, 33%, and 66%) 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) (table 1). In each plot, NDVI measurements were collected during each growing season using a Crop Circle ACS-

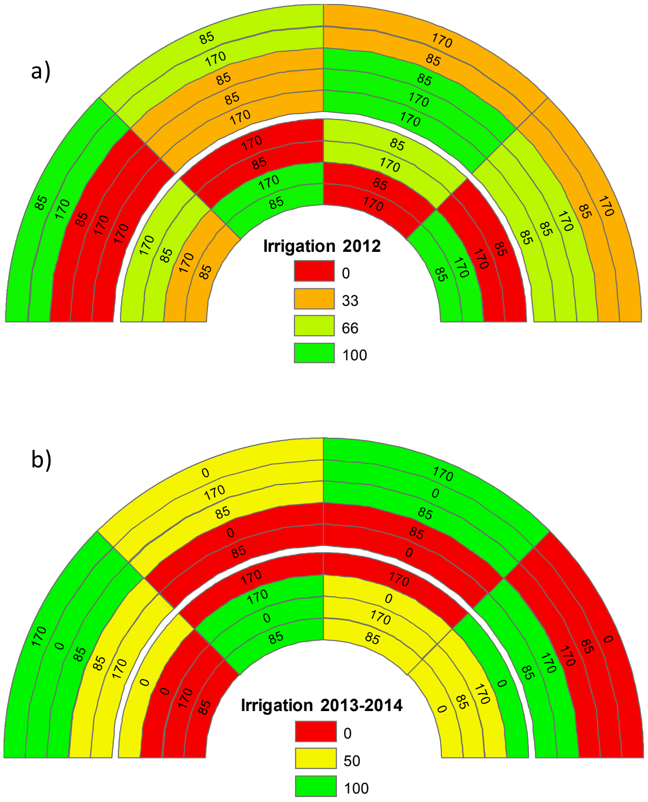

Figure 1. Plot plans for (a) 2012 and (b) 2013 and 2014 sorghum experiments. Irrigations are represented by the color scale and nitrogen rates are labeled in each plot. Within each irrigation/nitrogen treatment arc, the two sorghum varieties were randomized in an inner and outer arc.

Table 1. Seasonal rainfall, irrigation for the 100% treatment, crop evapotranspiration (ETc), planting and harvest dates for the 2012 to 2014 sorghum growing seasons.

Year	Seasonal Rainfall (mm)	Irrigation (mm)	ETc (mm)	Planting Date	N Application Dates	Harvest Date
2012	421.8	50.8	335.7	6/20/12	7/11, 7/19	10/22-23/12
2013	364.8	38.1	291.7	7/10/13	7/26, 8/26	11/18-19/13
2014	357.3	12.7	313.3	6/18/14	6/30, 8/7	10/1-3/14

430 (Holland Scientific, Lincoln, ND). The NDVI measurements were collected around mid-day at a distance of approximately 1-m above the plant canopy. NDVI was collected on 5, 2, and 5 dates in 2012, 2013, and 2014, respectively.

The experimental design in 2012 was a split-plot with irrigation rate as main plots and N levels as subplots. The experimental design in 2013 and 2014 was a split-split-plot with irrigation rate as the main plots and N levels as subplots and cultivars as the sub-subplots. The plot size was approximately 9.1 m wide by 45° of travel for the 137 m center pivot with four replicates (32 plots in 2012 and 72 plots in 2013 and 2014).

IRRIGATION SYSTEM

The center-pivot irrigation system had been modified to permit variable applications to individual areas as small as 9.1 × 9.1 m. The center-pivot radial length was divided into 13 segments, each 9.1 m in length. Variable-rate water applications were accomplished by using three manifolds in each segment, each with nozzles sized to deliver 1×, 2×, or 4× of a base application depth at their location along the center-pivot radius. The 12.7 mm irrigation rate was achieved when the outer tower was operated at 50% duty cycle. A more detailed description of the water delivery system was provided in Omary et al. (1997), and the control system was described in Camp et al. (1998).

FERTILIZER APPLICATIONS

All nitrogen fertilizer was applied via fertigation through the center-pivot system annually in two split applications. The first N application each year 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 UAN injection rate was varied proportionately based on the calculated water flow rate entering the pivot to achieve a constant UAN concentration in the water supplied to the pivot. This was achieved with a four-head, 24 VDC, variable-rate injection pump (model 40320, Ozawa R&D, Inc., Ontario, Ore.). The pump injection rate was controlled by varying the pump speed using a 0-5 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 in order to minimize irrigation water applications to non-irrigated plots. For this experiment, all nitrogen was delivered with 1.8-mm irrigation depth operating at 100% duty cycle. At the end of the nitrogen application, the system was again run in non-plot area to purge the system of nitrogen. 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. Fertilizer applied was 30 kg ha^{-1} P_2O_5 and 50 kg ha^{-1} K_2O in 2012, 30 kg ha^{-1} P_2O_5 and 80 kg ha^{-1} K_2O in 2013, and 25 kg ha^{-1} P_2O_5 and 60 kg ha^{-1} K_2O in 2014.

SOIL ANALYSIS

Soil samples were collected prior to planting in 2013 and 2014. The soil samples were placed in a laboratory oven, dried at 60°C for three days, and then weighed. A sample of the dried soil was analyzed for N content by the combustion method using a LECO 2000 CN analyzer (LECO Corp., St. Joseph, Mich.). Additionally, the soil samples were analyzed for NH_4-N, and NO_3-N using the water extraction method by ion chromatography (Dionex IC-200, Dionex Corp., Sunnyvale, Calif.) (Rhodes, 1996). Results of the pre-season soil analyses are shown in table 2.

HARVEST

The grain sorghum was harvested when the grain moisture was below 20%. Grain sorghum yields were determined by weighing the grain harvested from a 6.1-m length of two rows near the center of each plot using an Almaco plot combine (Almaco, Nevada, Iowa). Whole plot samples were weighed and a sub-sample from each plot was collected and dried at 60° C for three days to determine grain moisture concentration. Grain sorghum yields were reported as dry grain yields. After yields and total water applied to each treatment were determined, the water use efficiency (WUE) was calculated by dividing the mean plot yield by the total water applied (irrigation + rainfall). The WUE values were reported in units of kg grain ha^{-1} mm^{-1} of water applied.

STATISTICAL ANALYSES

Yield, WUE, and NDVI data were statistically analyzed for the treatment effects and year using analysis of variance (ANOVA). Means were separated by calculating the least significant difference (LSD) (SAS version 9.4, Proc GLM, Statistical Analysis System, SAS Institute, Cary, N.C.). All significant differences were evaluated at the 0.05 level.

RESULTS AND DISCUSSION

The cumulative seasonal rainfall, irrigation, and crop evapotranspiration values for all treatments are given in table 1 and figures 2-4. 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 (table 1). In 2012, irrigations were required to maintain SWP's greater than -30 kPa (at the 30 cm depth) during the early part of the growing season 30 to 50 DAP (growth stage 3, 8-leaf to stage 5, boot) and rainfall was adequate throughout the remainder of the growing season (fig. 5). In both 2013 and 2014, rainfall was generally adequate to maintain adequate SWP's except during the midpoint of the season from approximately 60 to 70 days after planting (stage 6, mid-bloom to stage 7, soft dough). During this time period, three irrigations in 2013 and one irrigation in 2014

Table 2. Pre-plant soil analysis of soil in 2013 and 2014.

Year	Depth (cm)	%N	NO_3-N + NH_4-N (mg/kg)	NO_3-N + NH_4-N (kg ha^{-1})
2013	0-15	0.076	18.6	27.9
	15-30	0.034	7.98	12.0
2014	0-15	0.12	38.4	57.6
	15-30	0.07	20.8	31.2

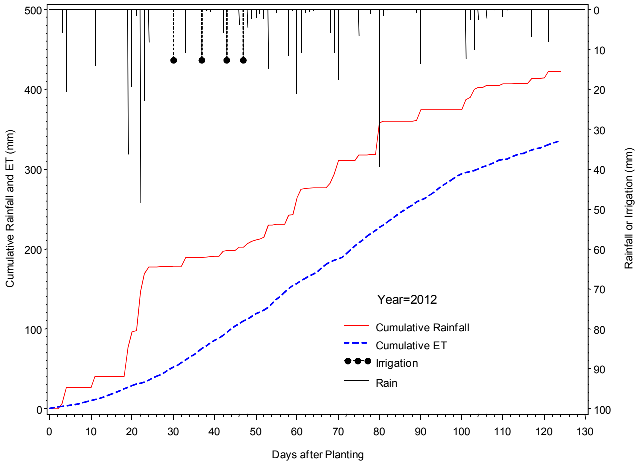

Figure 2. Cumulative rainfall, evapotranspiration, rain, and irrigation for the 2012 growing season.

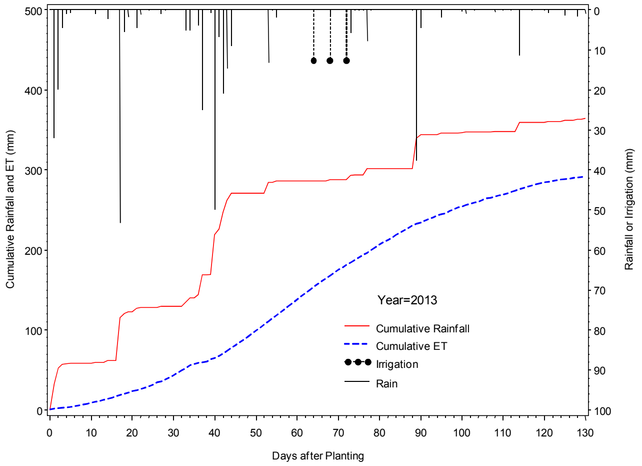

Figure 3. Cumulative rainfall, evapotranspiration, rain, and irrigation for the 2013 growing season.

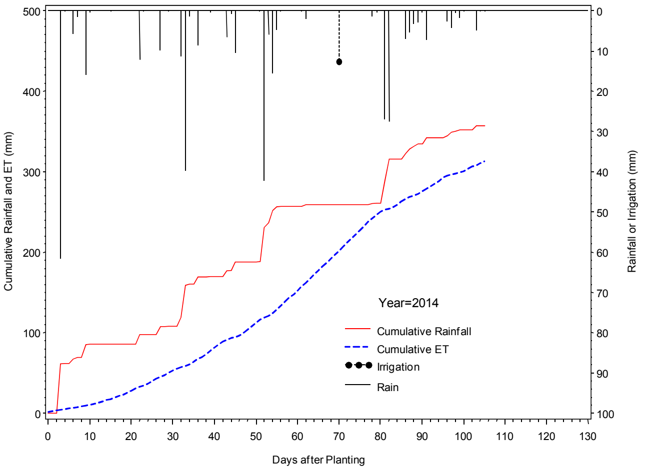

Figure 4. Cumulative rainfall, evapotranspiration, rain, and irrigation for the 2014 growing season.

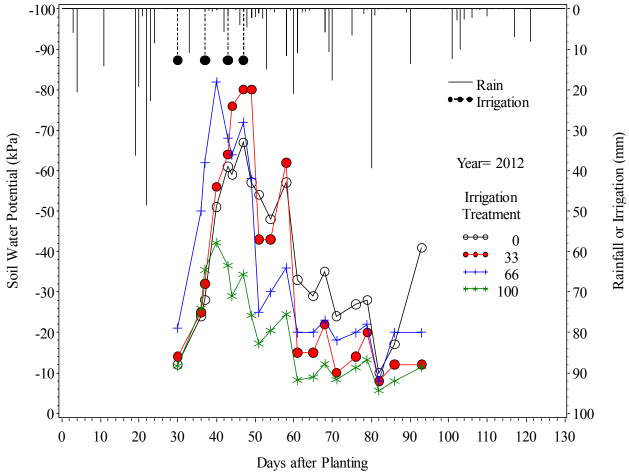

Figure 5. The 2012 30-cm soil water potentials for the 0, 33%, 66%, and 100% irrigation treatments.

were needed to maintain the SWP's above -30 kPa (figs. 6 and 7). The reduced rate irrigation during these time periods did have SWP values that were below -30 kPa levels, but after subsequent rainfalls, their SWP values increased and typically were above the -30 kPa threshold. Soil water potentials for the 60-cm depth followed similar trends to those of the 30-cm depth (data not shown).

SORGHUM YIELD

In 2012, the mean grain sorghum yield was 2.8 Mg ha^{-1}. The mean treatment yields for the four irrigation and two nitrogen application rates are shown in table 3. An analysis of variance for the 2012 year indicated no significant differences in grain yield for irrigation application, nitrogen application rates, or the interactions between the irrigation and nitrogen rates.

In 2013, the individual mean grain sorghum yield was 3.3 Mg ha^{-1} while in 2014, the mean yield was 3.1 Mg ha^{-1}. Overall treatment yield for the two years are shown in table 4. An ANOVA for the 2013 and 2014 seasons indicated no significant differences in sorghum grain yields for the three irrigation or three nitrogen application rates (table 5). Furthermore, interaction between the variety, irrigation, and nitrogen treatments were not significant.

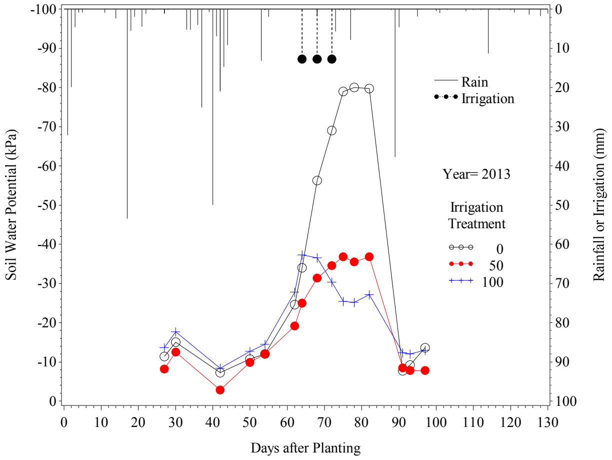

Figure 6. The 2013 30-cm soil water potentials for the 0, 50%, and 100% irrigation treatments.

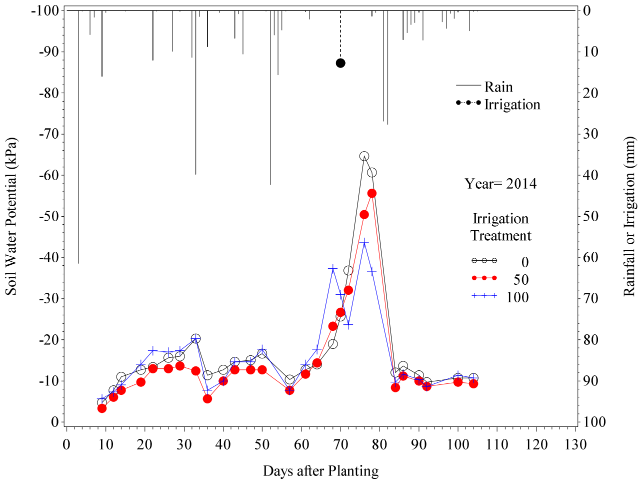

Figure 7. The 2014 30-cm soil water potentials for the 0, 50%, and 100% irrigation treatments.

Additionally, we combined data from 2012-2014 for the Dekalb variety, fertilized at 85 and 170 kg N ha^{-1} for the fully irrigated (100%) and non-irrigated treatments and reanalyzed the data for the entire 3-year study (table 6). No significant differences among the irrigation or nitrogen treatments for the sorghum grain yields occurred (table 7).

Overall, our sorghum grain yields were below those reported in the literature for Kansas (~7 Mg ha^{-1}, Klocke et al., 2012) and for Texas (5 to 7 Mg ha^{-1}, O'Shaughnessy et al., 2012) where supplemental irrigation is often necessary for production. A study in a more humid region by Bruns (2015) in Mississippi reported grain sorghum yields of 5.2 to 5.3 Mg ha^{-1}. Yang et al. (2001), in south Texas, reported sorghum grain yields similar to ours with yields ranging from 2.3 to 4.7 Mg ha^{-1}. Our study yields may have been impacted due to late season bird damage and delayed harvest until the crop was dry enough to harvest with a plot combine (post-harvest drying equipment was not available).

Unlike other reported studies, we observed no increase in yield response due to increasing nitrogen applications. Abunyewa et al. (2017) reported a quadratic relationship of increasing grain sorghum yields with nitrogen fertilizer applications. Our study site had been in a 4-year highly fertilized bermudagrass production study (Stone et al., 2012) and a 1-year flax study in the previous 5 years, and the soil in this experiment may have had adequate holdover nitrogen to produce an adequate sorghum crop. In a companion study, Sigua et al. (2017) reported the preseason 0- 30 cm total inorganic soil nitrogen values of approximately 40 and 89 kg N ha^{-1} in 2013 and 2014, respectively (table 2). Franzlueb-

Table 3. The 2012 mean sorghum grain yields and water use efficiencies for the four irrigation and two nitrogen treatments.

	Nitrogen						Nitrogen					
	85		170		Mean		85		170		Mean	
	Yield (Mg ha^{-1})						Water Use Efficiency (kg ha^{-1} mm^{-1})					
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Water												
0	3.0	0.7	2.8	0.4	2.9	0.5	6.4	1.5	6.0	0.8	6.1	1.0
33	2.8	0.6	2.9	0.5	2.9	0.5	6.0	1.2	6.1	1.0	6.0	1.0
66	2.4	0.6	2.6	0.2	2.5	0.5	5.0	1.3	5.6	0.5	5.2	1.0
100	3.3	0.4	2.8	0.3	3.1	0.4	7.0	0.9	6.0	0.6	6.5	0.9
Mean	2.9	0.6	2.8	0.3	2.8	0.5	6.1	1.3	5.9	0.7	6.0	1.0

Table 4. Mean sorghum grain yields for the 2013 and 2014 variety, irrigation, and nitrogen treatments.

			Water							
			0		50		100		Overall Mean	
			Yield (Mg ha^{-1})							
Year	Variety		Mean	Std	Mean	Std	Mean	Std	Mean	Std
2013	DeKalb	Nitrogen								
		0	3.3	1.0	3.0	0.9	3.5	0.5	3.3	0.8
		85	2.8	0.4	3.3	0.7	3.3	0.8	3.1	0.6
		170	3.3	1.0	3.0	0.3	3.2	0.9	3.2	0.7
		Mean	3.1	0.8	3.1	0.6	3.4	0.7	3.2	0.7
	Pioneer	Nitrogen								
		0	3.2	0.1	3.5	0.1	3.4	0.6	3.4	0.3
		85	4.0	0.7	3.8	0.3	3.5	0.6	3.8	0.5
		170	3.4	0.8	3.1	0.4	3.5	0.6	3.3	0.6
		Mean	3.5	0.6	3.5	0.4	3.5	0.5	3.5	0.5
2014	DeKalb	Nitrogen								
		0	3.5	1.2	2.6	0.2	2.8	1.3	3.0	1.0
		85	3.4	1.1	3.0	0.9	3.2	0.6	3.2	0.8
		170	3.1	1.0	2.9	0.6	2.8	0.9	2.9	0.8
		Mean	3.3	1.0	2.8	0.6	2.9	0.9	3.0	0.8
	Pioneer	Nitrogen								
		0	3.0	1.3	3.1	0.4	2.8	1.5	3.0	1.0
		85	3.5	1.0	3.1	1.1	3.6	0.3	3.4	0.8
		170	3.1	0.7	3.5	0.5	3.1	0.9	3.2	0.6
		Mean	3.2	0.9	3.2	0.7	3.2	1.0	3.2	0.8
	Overall Mean		3.3	0.8	3.2	0.6	3.2	0.8	3.2	0.7

Table 5. Analysis of variance for the 2013 and 2014 study years for sorghum variety, irrigation rate, and nitrogen application rate.

Source	DF	Yield Pr > F	Water Use Efficiency Pr > F
Nitrogen	2	0.43	0.43
Water	2	0.75	0.25
Water*Nitrogen	4	0.99	0.99
year	1	0.15	0.74
Nitrogen*year	2	0.80	0.80
Water*year	2	0.67	0.93
Water*Nitrogen*year	4	0.75	0.75
Variety	1	0.14	0.14
Variety*Nitrogen	2	0.62	0.62
Variety*Water	2	0.81	0.81
Variety*Water*Nitrogen	4	0.81	0.81
Variety*year	1	0.75	0.76
Variety*Nitrogen*year	2	0.78	0.78
Variety*Water*year	2	0.63	0.61
Variety*Water*Nitrogen*year	4	0.95	0.95

bers et al. (2000) estimated that in the first 10 years of production, bermudagrass pastures could accumulate up to 16 kg N ha^{-1} per year in the 0-200 mm soil depth. This soil N accumulation along with the measured preseason N could be available for the sorghum to utilize. Additionally, the relatively low harvested sorghum yields each year may have contributed N not utilized in crop production. To further investigate this result, we analyzed in-season normalized difference vegetative indices (NDVI) measurements taken throughout the season. The NDVI measurements have been used in the precision agriculture to generally access the status of crops for nutrient status and/or variable rate nutrient applications. We selected the NDVI measurements near growth stage 3 (growing-point differentiation stage, approximately 30 days after emergence and representing the change in the growing point from vegetative to reproductive growth; Vanderlip and Reeves, 1972). The NDVI readings at this growth stage were similar to measurements taken by Moges et al. (2007) for calculating in-season estimation of grain sorghum yield potential. In 2012, there were no significant differences in NDVI measurements for the irrigation and nitrogen treatments. In 2013, the NDVI values for the 85 and 170 kg N ha^{-1} treatments were significantly higher than the 0 kg N ha^{-1} treatment. The 2013 NDVI values were 0.61, 0.68, and 0.68 (LSD=0.02) for the 0, 85, and 170 kg N ha^{-1} treatments, respectively. In 2014 the NDVI values were 0.80, 0.81, and 0.81 (LSD = 0.01) for the 0, 85, and 170 kg N ha^{-1} treatments, respectively. These NDVI results help explain the non-significant yields between the 80 and 170 kg N ha^{-1} treatments in all years and also for all treatments in 2012 and 2014. Similar NDVI readings showed that the treatments were not significantly different in their nitrogen fertilizer status (Raun et al., 2002; Holland and Schepers, 2010; Thompson et al., 2015).

Table 7. Analysis of variance for all three (2012-2014) study years for the common variety, DeKalb, with 0 and 100% irrigation rates, and 85 and 170 lb N per acre.

Source	DF	Yield Pr > F	Water Use Efficiency Pr > F
Nitrogen	1	0.51	0.57
Water	1	0.83	0.41
Water*Nitrogen	1	0.53	0.56
year	2	0.83	0.04
Nitrogen*year	2	0.61	0.62
Water*year	2	0.67	0.86
Water*Nitrogen*year	2	0.88	0.87

WATER USE EFFICIENCY

In 2012, the overall WUE was 6.0 kg ha^{-1} mm^{-1} of water received (rainfall + irrigation) and varied among the treatments from 5 to 7 kg ha^{-1} mm^{-1} (table 3). In 2013 and 2014, the overall WUE was 8.7 kgha^{-1} mm^{-1} and varied from 7.1 to 10.8 kg ha^{-1} mm^{-1} (table 8). In both the 2012 and 2013-2014 studies, there were no significant differences in WUE between irrigation or nitrogen treatments. However, in the combined 2012-2014 dataset, there was a significant WUE difference for the year of the study, with the 2012 year having significantly lower WUE of 6.7 kg ha^{-1} mm^{-1} compared to the 2013 and 2014 WUE's of 8.2 and 7.7 kg ha^{-1}/mm^{-1}, respectively (table 7). The 2012 WUE values were lower because of higher total seasonal rainfall. Our calculated WUE values for the grain sorghum were intermediate between those published by O'Shaughnessy et al. (2012) which ranged from 4.5 for non-irrigated to 17 kg ha^{-1} mm^{-1} for an 80% irrigated study in Texas.

SUMMARY AND CONCLUSIONS

Grain sorghum was grown in 2012, 2013, and 2014 to investigate the potential for irrigation to increase yields in the humid SE United States. Supplemental irrigation was required

Table 6. Mean sorghum grain yields and water use efficiencies for the 2012-2014 common variety, irrigation, and nitrogen treatments.

			Water						Water					
			0		100		Mean		0		100		Mean	
			Yield (Mg ha^{-1})						Water Use Efficiency (kg ha^{-1} mm^{-1})					
Year	Variety		Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
2012	DeKalb	Nitrogen												
		85	3.0	0.7	3.3	0.4	3.2	0.5	7.1	1.6	7.0	0.9	7.1	1.1
		170	2.8	0.4	2.8	0.3	2.8	0.3	6.7	0.9	6.0	0.6	6.3	0.8
		Mean	2.9	0.5	3.1	0.4	3.0	0.4	6.9	1.2	6.5	0.9	6.7	1.0
2013	DeKalb	Nitrogen												
		85	2.8	0.4	3.3	0.8	3.1	0.6	7.6	1.1	8.3	2.0	7.9	1.5
		170	3.3	1.0	3.2	0.9	3.2	0.8	9.0	2.7	8.0	2.2	8.5	2.3
		Mean	3.0	0.7	3.3	0.8	3.1	0.7	8.3	2.0	8.1	1.9	8.2	1.9
2014	DeKalb	Nitrogen												
		85	3.4	1.1	3.2	0.6	3.3	0.8	9.6	3.1	8.5	1.7	9.0	2.3
		170	3.1	1.0	2.8	0.9	3.0	0.9	8.7	2.8	7.7	2.5	8.2	2.5
		Mean	3.3	1.0	3.0	0.7	3.1	0.8	9.1	2.7	8.1	2.0	8.6	2.3
	Overall Mean		3.0	0.7	3.1	0.6	3.1	0.7	8.0	2.1	7.5	1.7	7.7	1.9

Table 8. Mean water use efficiencies for the 2013 and 2014 variety, irrigation, and nitrogen treatments.

			Water							
			0		50		100		Overall Mean	
			Water Use Efficiency (kg ha^{-1} mm^{-1})							
Year	Variety		Mean	Std	Mean	Std	Mean	Std	Mean	Std
2013	DeKalb	Nitrogen								
		0	9.1	2.9	7.9	2.4	8.8	1.2	8.6	2.0
		85	7.6	1.1	8.6	1.9	8.3	2.0	8.2	1.5
		170	9.0	2.7	7.9	0.7	8.0	2.2	8.3	1.9
		Mean	8.6	2.2	8.1	1.6	8.4	1.6	8.3	1.8
	Pioneer	Nitrogen								
		0	8.8	0.4	9.1	0.3	8.4	1.5	8.8	0.8
		85	10.8	1.9	9.9	0.7	8.7	1.4	9.8	1.5
		170	9.3	2.1	8.0	1.0	8.7	1.5	8.7	1.5
		Mean	9.7	1.7	9.0	1.0	8.6	1.3	9.1	1.4
2014	DeKalb	Nitrogen								
		0	9.8	3.4	7.1	0.5	7.5	3.4	8.1	2.8
		85	9.6	3.1	8.2	2.4	8.5	1.7	8.8	2.2
		170	8.7	2.8	7.9	1.6	7.7	2.5	8.1	2.1
		Mean	9.4	2.8	7.7	1.6	7.9	2.3	8.3	2.3
	Pioneer	Nitrogen								
		0	8.5	3.5	8.5	1.1	7.6	4.1	8.2	2.8
		85	9.8	2.8	8.5	3.1	9.8	0.7	9.4	2.2
		170	8.8	2.0	9.6	1.3	8.3	2.3	8.9	1.8
		Mean	9.0	2.5	8.9	1.8	8.6	2.6	8.8	2.3
	Overall Mean		9.2	2.3	8.4	1.6	8.4	2.0	8.7	2.0

for 4, 3, and 1 irrigation events in 2012, 2013, and 2014, respectively, to maintain soil water potential above -30 kPa in the 100% treatments. However, these water applications did not increase grain sorghum yields. Additionally, we found no significant difference in grain yield for increasing nitrogen application. This lack of response to nitrogen applications may have been related to adequate supplies in the soil from previous crops. Our results are similar to previous work from the mid-South United States in that irrigation did not increase sorghum grain yields above those of rainfed, and suggest that there would be little benefit for supplemental irrigation for sorghum production in the U.S. eastern coastal plain.

REFERENCES

Abunyewa, A. A., Ferguson, R. B., Wortmann, C. S., & Mason, S. C. (2017). Grain sorghum nitrogen use as affected by planting practice and nitrogen rate. *J. Soil Sci. Plant Nutrition, 17*, 155-166. https://doi.org/10.4067/S0718-95162017005000012

Allen, R. G., Pereira, L. S., Smith, M., & Raes, D. (1998). Crop evapotranspiration. FAO Irrigation and Drainage Paper No. 56. Rome, Italy: United Nations FAO.

Assefa, Y., & Staggenborg, S. A. (2010). Grain sorghum yield with hybrid advancement and changes in agronomic practices from 1957 through 2008. *Agron. J., 102*(2), 703-706. https://doi.org/10.2134/agronj2009.0314

Bordovsky, J. P., & Lyle, W. M. (1996). LEPA irrigation of grain sorghum with varying water supplies. *Trans. ASAE, 39*(6), 2033-2038. https://doi.org/10.13031/2013.27706

Bruns, H. A. (2015). Irrigation, seeding rates, and row type effects on grain sorghum in the midsouth. *Agron. J., 107*(1), 9-12. https://doi.org/10.2134/agronj14.0297

Camp, C. R., & Sadler, E. J. (2002). Irrigation, deep tillage, and nitrogen management for a corn-soybean rotation. *Trans. ASAE, 45*(3), 601-608. https://doi.org/10.13031/2013.8824

Camp, C. R., Sadler, E. J., Evans, D. E., Usrey, L. J., & Omary, M. (1998). Modified center pivot system for precision management of water and nutrients. *Appl. Eng. Agric., 14*(1), 23-31. https://doi.org/10.13031/2013.19362

Franzluebbers, A. J., Stuedemann, J. A., Schomberg, H. H., & Wilkinson, S. R. (2000). Soil organic C and N pools under long-term pasture management in the southern piedmont USA. *Soil Biol. Biochem., 32*(4), 469-478. https://doi.org/10.1016/S0038-0717(99)00176-5

Hatfield, J. L., Gitelson, A. A., Schepers, J. S., & Walthall, C. L. (2008). Application of spectral remote sensing for agronomic decisions. *Agron. J., 100*, S-117-S-131. https://doi.org/10.2134/agronj2006.0370c

Hibberd, D. E., & Hall, B. D. (1990). The responses of maize and grain sorghum hybrids to nitrogen fertiliser in south east Queensland. *Australian J. Exp. Agric., 30*(6), 825-831. https://doi.org/10.1071/EA9900825

Holland, K. H., & Schepers, J. S. (2010). Derivation of a variable rate nitrogen application model for in-season fertilization of corn. *Agron. J., 102*(5), 1415-1424. https://doi.org/10.2134/agronj2010.0015

Klocke, N. L., Currie, R. S., Tomsicek, D. J., & Koehn, J. W. (2012). Sorghum yield response to deficit irrigation. *Trans. ASABE, 55*(3), 947-955. https://doi.org/10.13031/2013.41526

Moges, S. M., Girma, K., Teal, R. K., Freeman, K. W., Zhang, H., Arnall, D. B.,... Raun, W. R. (2007). In-season estimation of grain sorghum yield potential using a hand-held optical sensor. *Archives Agron. Soil Sci., 53*(6), 617-628. https://doi.org/10.1080/03650340701597251

Murphy-Brown. (2012). Sorghum program. Retrieved from http://mbgrain.com/wp-content/uploads/2012/03/MurphyBrown_SorghumProgram_Draftv3.pdf

Omary, M., Camp, C. R., & Sadler, E. J. (1997). Center pivot irrigation system modification to provide variable water application depths. *Appl. Eng. Agric., 13*(2), 235-239. https://doi.org/10.13031/2013.21604

O'Shaughnessy, S. A., Evett, S. R., Colaizzi, P. D., & Howell, T. A. (2012). Grain sorghum response to irrigation scheduling with the time-temperature threshold method and deficit irrigation levels. *Trans. ASABE, 55*(2), 451-461. https://doi.org/10.13031/2013.41395

Peele, T. C., Beale, O. W., & Lesesne, F. F. (1970). The physical properties of some South Carolina soils. Tech. Bull. 1037. Clemson, SC: South Carolina Agricultural Experiment Station, Clemson University.

Raun, W. R., Solie, J. B., Johnson, G. V., Stone, M. L., Mullen, R. W., Freeman, K. W.,... Lukina, E. V. (2002). Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. *Agron. J., 94*(4), 815-820. https://doi.org/10.2134/agronj2002.8150

Rhodes, J. D. (1996). Salinity: Electrical conductivity and total dissolved solids. In D. Sparks (Ed.), *Methods of soil analysis. Part 3.* (pp. 417-435). Madison, WI: SSSA.

Sheridan, J. M., Knisel, W. G., Woody, T. K., & Asmussen, L. E. (1979). Seasonal variation in rainfall and rainfall-deficit periods in the southern coastal plain and flatwoods regions of Georgia. Bull. 243. Athens: University Georgia Agricultural Experiment Station.

Sigua, G. C., Stone, K. C., Bauer, P. J., & Szogi, A. A. (2018). Biomass and nitrogen-use efficiency of grain sorghum (*Sorghum bicolor* L.) 1 with nitrogen and supplemental irrigation in coastal plain region, USA. *Agron. J.* doi: 10.2134/agronj2017.09.0533.

Stone, K. C., Bauer, P. J., Andrae, J., Busscher, W. J., Millen, J. A., Strickland, E. E., & Evans, D. E. (2012). Irrigation and nitrogen impact on bermudagrass yield response in the southeastern coastal plain. *Trans. ASABE, 55*(3), 969-978. https://doi.org/10.13031/2013.41528

Swick, R. A. (2011). Global feed supply and demand. *Recent Advances in Animal Nutrition-Australia, 18*, 1-8.

Thompson, L. J., Ferguson, R. B., Kitchen, N., Frazen, D. W., Mamo, M., Yang, H., & Schepers, J. S. (2015). Model and sensor-based recommendation approaches for in-season nitrogen management in corn. *Agron. J., 107*(6), 2020-2030. https://doi.org/10.2134/agronj15.0116

USDA-NASS. (2017). USDA quick stats. Washington, DC: USDA-NASS. Retrieved from https://quickstats.nass.usda.gov/

Vanderlip, R. L., & Reeves, H. E. (1972). Growth stages of sorghum. *Agron. J., 64*(1), 13-16. https://doi.org/10.2134/agronj1972.00021962006400010005x

Walter, I. A., Allen, R. G., Elliott, R., Jensen, M. E., Itenfisu, D., Howell, T. A.,... Martin, D. (2000). ASCE's standardized reference evapotranspiration equation. In R. G. Evans, B. L. Benham, & T. P. Trooien (Ed.), *Proc. 4th National Irrigation Symp.* (pp. 209-215). St. Joseph, MI: ASAE.

Yang, C., Everitt, J. H., & Bradford, J. M. (2001). Comparisons of uniform and variable rate nitrogen and phosphorus fertilizer applications for grain sorghum. *Trans. ASAE, 44*(2), 201-209. https://doi.org/10.13031/2013.4676