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Cotton Response to Irrigation and Nitrogen Source in Differing Mid-South Soils

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ABSTRACT

Cotton (*Gossypium hirsutum* L.) irrigation management is challenging in a humid region, where rainfall is unpredictable and soils range from coarse-textured to fine-textured. Loss of applied N in coarse-textured soils receiving high amounts of irrigation is a concern for producers. This study was conducted to improve cotton irrigation recommendations in differing soils in the Mid-South and to evaluate the effect of a controlled release N fertilizer on N uptake and yield of cotton grown in different soils and irrigation regimes. The effects of irrigation initiation/rate and N source on cotton yield and N uptake were investigated in Jackson, TN, in soils that differed in texture. In two wet growing seasons, cotton grown in deep silt loam soils did not respond to irrigation. Irrigation of cotton grown in coarse-textured soil could be delayed until bloom without yield loss, but then needed a supplemental rate of 38.1 mm wk^{-1} to optimize yield. These results reveal a clear benefit to managing irrigation separately in differing soils, when possible. Cotton receiving ammonium nitrate (AN) generally yielded higher than cotton receiving controlled release N fertilizer. However, cotton yields were similar between N sources in coarse-textured soils. Our results support the notion that cotton grown in differing soils would benefit from multiple irrigation decisions, and indicate no apparent yield or N uptake benefit from the use of a controlled release N fertilizer in no-till cotton.

Core Ideas

- Cotton yield and N uptake are examined across irrigation regimes, N sources, and soils.
- In two wet growing seasons, cotton in silt loam soils did not respond to irrigation.
- Cotton in coarse-textured soils required irrigation beginning at bloom in wet years.
- Use of controlled release N resulted in generally lower yields than ammonium nitrate .
- In coarse-textured soils, cotton yielded similarly between N sources.

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Nitrogen and water deficiency have the potential to severely limit cotton yield and proper management of these resources is important for the economic and environmental sustainability of cotton production (Hake et al., 1991). Cotton in the Mid-South is grown in soils with varying texture and water holding capacity (WHC), which has the potential to affect the response of cotton to irrigation and N management.

IRRIGATION

Management of cotton irrigation in the Mid-South is dependent on yearly climactic conditions. Cotton response to irrigation initiation timing and rate of application in a silt loam soil was studied in Tennessee from 2006 to 2009 (Gwathmey et al., 2011). In 2 yr, a supplemental rate of 25.4 mm wk^{-1} optimized yield, in a drought year, 38.1 mm wk^{-1} was necessary, and in the wettest year no yield increase was observed from irrigating. In this silt loam soil, irrigation delayed until bloom or after optimized yields. Similarly, Barber and Francis (2011) found that irrigation should be initiated around first bloom to optimize yield and that 2 to 3 wk after first bloom was a critical time to have adequate soil moisture. Jalota et al. (2006) also concurred that flowering is the most sensitive stage of cotton to water stress with respect to yield. Huber et al. (1999) found a rate of 25.4 mm wk^{-1} to significantly boost yields in the majority of years in a silt loam soil, in the Mid-South.

Cotton grown in coarse-textured, low WHC soil is expected to respond differently to irrigation, compared to that in high WHC soil. Duncan (2012) studied cotton irrigation in soils of low and high WHC in Tennessee and found distinct differences in irrigation management needed for each soil. A higher rate of application, 38.1 mm wk^{-1} was needed to optimize yields in coarse-textured soils. Irrigation was also needed earlier in low WHC soils. Initiating irrigation at first square was typically the optimal timing for low WHC soils. DeTar (2008) noted that coarse-textured soils require higher water input to maintain adequate soil moisture; therefore, the allowable depletion of soil moisture, past which yield will likely be restricted, is smaller in coarse-textured soils.

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Abbreviations: AN, ammonium nitrate; ESN, Environmentally Smart Nitrogen; NUE, nitrogen use efficiency; WHC, water holding capacity.

NITROGEN

High water input, especially in coarse-textured soils, can potentially cause N loss through leaching, while excess water can create more frequently saturated conditions in fine-textured soils leading to volatilization and/or denitrification losses (Rochester, 2012; Wilson et al., 2010). As such, N source can have a significant effect on cotton yield across soils and various irrigation regimes. Primary considerations for effectiveness of N application are amount and timing. Cotton is sensitive to over- and under-fertilization (Hake et al., 1991). Cotton N uptake is most rapid during the first few weeks of flowering (Guthrie et al., 1994), meaning this is a critical time for plant available N.

Controlled release N fertilizers have the potential to decrease the amount of fertilizer N released into the soil at a given time, as well as reducing the amount of time fertilizer N resides in the soil unprotected (Chen et al., 2008; Oosterhuis and Howard, 2008). These factors govern the susceptibility of fertilizer N to loss. Controlled release N fertilizers have accordingly shown potential to increase nitrogen use efficiency (NUE) (Gandeza et al., 1991; Shoji et al., 2001; Wilson et al., 2010). Controlled release N fertilizer should be evaluated as a potential method to avoid N loss and optimize N utilization in irrigated cotton, especially in coarse-textured soils.

Environmentally Smart Nitrogen (ESN) is a controlled release, polymer-coated urea fertilizer (Agrium, Inc., Loveland, CO). With adequate antecedent moisture conditions, N release from ESN is regulated primarily by temperature, with approximately an 80% release between 30 and 60 d after application at 23°C (Golden et al., 2011). Environmentally Smart Nitrogen has been shown to achieve corn (*Zea mays* L.) yields comparable with other N sources, with potential to improve NUE (Mozaffari et al., 2012a; Cahill et al., 2010). In potato (*Solanum tuberosum* L.) production in coarse-textured soils, a system requiring high water throughput, ESN is an especially effective N source, maintaining similar yields with a single application to multiple applications of conventional fertilizer and improving N recovery (Wilson et al., 2009; Wilson et al., 2010). Cotton fertilized with ESN yielded similarly to urea in a Marvel silt loam in Arkansas (Mozaffari et al., 2012b). Fertilization of cotton with ESN warrants further examination across multiple soils and irrigation regimes. Cotton can lose yield due to water and N stress, and soil texture and WHC have a great impact on susceptibility to each (Zelinski and Grimes, 1995).

Interactions between irrigation and N are often observed in cotton research, with soil being as uniform as possible (Boquet and Coco, 1986; Bronson et al., 2001, 2006; Bronson, 2008; McConnell et al., 1989; Vories et al., 2014; Pettigrew and Zeng, 2014; Singh et al., 2010). Often, these interactions are among varying rates of water application and levels of N application. Interactions are also observed between irrigation and soils, with N source and rate held constant (Vories et al., 2015; Jalota et al., 2006; Tolk and Howell, 2010). Interactions between soils, irrigation, and N are complex. Li et al. (2002) conducted field-scale research to examine the effect of differing levels of water input and N application rates on yield across a field that varied in soil type. Li et al. (2002) observed and discussed three-way interactive effects of soil, irrigation, and N input, noting the heavy influence of soil and interdependency of irrigation and N rate effects. This research is unique in that it examines soils, irrigation, and N sources simultaneously using irrigation regimes with varying initiation timings and application rates across different N sources.

The main objectives of this study were to evaluate: (i) effect of deficit irrigation treatments on cotton yield in different soils; (ii) the potential of a controlled release N fertilizer to benefit cotton yield and N uptake, and (iii) interactions between irrigation, N source, and soil.

MATERIALS AND METHODS

The research was conducted at the West Tennessee Research and Education Center (WTREC) in Jackson, TN, during the 2013 and 2014 growing seasons. The experiment was arranged in a randomized complete block (RCBD) split-plot design. The study was blocked on soil, based on depth to sand and water holding capacity. Cotton plots were six rows wide, with 96.5 cm row spacing, and 9.1 m long. The four center rows of each whole plot were harvest rows, while the outer two rows served as border rows. Each of these plots was randomly assigned an irrigation treatment, within soil block. Whole plots were then split, and half the plot received AN fertilizer, while the other half received ESN. Each subplot, therefore, consisted of two harvest rows and one border row nearest to the next whole plot. Fertilizer treatments were assigned randomly within each whole plot. Nitrogen sources were broadcast applied over each three-row subplot from outside row middle to outside row middle, such that N sources were adjacent to one another between subplots.

Cotton (cultivar Phytogen 375) was direct seeded on 8 May 2013 and 6 May 2014 in a no-till cropping system that has been cropped in cotton since 2010. All areas of the study site tested high in P and K in both years according to University of Tennessee recommendations, so no additional fertilizer was added. Nitrogen fertilizer was broadcast 2 wk after planting. Ammonium nitrate and ESN were both applied at a rate of 90 kg N ha^{-1}. The cotton crop was managed according to University of Tennessee recommendations with no differential applications by soil of growth regulator, pesticide applications, etc. This most closely replicates a producer's situation, where multiple soils exist in the same field.

A location with variation in soils was chosen for this study. Soils of the test site were a Ruston-Dexter-Lexington complex. These soils are classified as fine-loamy, siliceous, semiactive, thermic Typic Paleudults; fine-silty, mixed, active, thermic Ultic Hapludalfs; and fine-silty, mixed, active, thermic Ultic Hapludalfs, respectively. Each of these soils share a silt cap over sandy soil, but they differ significantly in depth to sandy soil. Depth and textural consistency of the silt layer impacted WHC. Soil delineations were made by a combination of ground-penetrating radar, electrical conductivity measurements, and soil cores (Duncan, 2012). Seven soil blocks were delineated for the experiment, with average WHCs ranging from 5.8 to 15.8 cm m^{-1}. Depth of the silt layer before reaching sandy soil varied from <70 cm in the low WHC soil block to >120 cm in the highest WHC soil block. The experiment was established in the same location in both years, so soil blocks were the same for the entire study. Irrigation treatments were randomized each year within each soil block, and N source was randomized within each irrigation treatment plot.

Seven irrigation treatments were used as part of an ongoing deficit irrigation study (Table 1). Irrigation treatments varied in rate of water application, as well as timing of irrigation initiation. Irrigation was applied through a surface drip irrigation system, which achieved varying irrigation rates through use of three different drip tape sizes. One line of drip tape was laid per row of cotton. To achieve 12.7, 25.4, and 38.1 mm wk^{-1}, drip tapes with flow rates of 0.076, 0.150, and 0.240 L per hour per 100 m were used. This allowed the entire system to run the same amount of time, while applying three different rates. Irrigation was applied 3 d wk^{-1}, Mondays, Wednesdays, and Fridays, and was adjusted for rainfall. Irrigation time, adjusted for rainfall, was based on the 25.4 mm wk^{-1} treatment. With no rainfall, the irrigation system was run long enough to apply 10.2 mm on Monday, 7.6 mm on Wednesday, and 7.6 mm on Friday, in the 25.4 mm wk^{-1} treatment. This schedule was adjusted for rainfall to achieve as close to 25.4 mm wk^{-1} as possible. Some rainfall events brought several centimeters in a short amount of time, so response to these events was based on estimated effectiveness or infiltration of rainfall. All irrigated plots received supplemental water as required until cracked boll.

Table 1. Irrigation treatments and applied water per treatment in both years of study.

Treatment no.	Initiation	Rate	Total water applied 2013	Total water applied 2014
		mm wk^{-1}	mm	mm
1	Square	38.1	128.8	191.3
2	Square	25.4	85.9	127.5
3	Square	12.7	42.9	63.8
4	Bloom	38.1	92.7	145.3
5	Bloom	25.4	61.7	96.8
6	Square, Bloom	12.7, 38.1	103.4	160.5
7	Dryland	0	0.0	0.0

To monitor the N status of cotton throughout the growing season, leaf samples were taken at first flower and 5 wk past first flower, mid-late bloom. Leaf samples were taken from plots in irrigation treatments 1, 5, 6, and 7 and from all combinations of soil block and N source. Dates of sampling were 8 July and 14 August in 2013 and 17 July and 22 August in 2014. The uppermost mature leaf on a given plant was sampled, the petiole was discarded, and 20 leaves per plot were collected. Samples were sent to the University of Tennessee Soil Plant and Pest Center, where they were analyzed for total combustible N content.

Both years of this study could be considered wet years, even for the humid Mid-South. In 2013, the site received 546 mm of rain from planting to harvest, 8 May to 8 October (Table 2), 170 mm of which fell from square to cracked boll. Rainfall was evenly distributed and growing conditions were good in 2013, contributing to high yields. In 2014, the site received 831 mm of rain from planting to harvest, 6 May to 5 October, of which 230 mm fell from square to cracked boll. In 2014, rainfall was more sporadic, and large portions of the total came in several large events.

Table 2. Weekly and cumulative rainfall and crop water use for the two growing seasons. Seasonal rainfall from standard NOAA weather station less than 400 m from field and 30 yr rainfall data from NOAA National Climactic Data Center. Crop water use, or evapotranspiration (ET), calculated using the Turc method and FAO crop coefficients.

Weeks from planting	2013 Rainfall	2013 Crop water use	2014 Rainfall	2014 Crop water use	30-Yr avg. Rainfall	30-Yr avg. Crop water use
	mm					
1	41.9	8.6	10.7	9.7	27.6	10.1
2	18.3	10.7	79.5	10.2	27.9	10.3
3	75.7	11.4	3.3	10.7	29.9	10.7
4	66.0	10.7	12.2	10.9	30.7	11.1
5	10.9	13.0	87.9	14.2	32.6	14.8
6	21.3	20.6	120.1	18.8	30.5	19.2
7	36.8	21.8	1.0	23.4	26.2	23.8
8	4.1	30.0	15.5	27.9	26.8	28.3
9	18.0	27.7	70.4	32.5	24.4	32.7
10	12.2	36.3	13.2	37.1	34.8	37.1
11	28.7	34.0	58.2	37.6	16.9	37.6
12	50.8	30.7	4.8	37.3	30.3	37.3
13	13.7	27.7	0.0	36.8	24.0	36.8
14	14.7	26.9	58.9	36.3	24.1	36.1
15	19.6	28.7	7.1	35.6	17.5	35.3
16	7.6	33.8	63.0	34.5	12.9	34.2
17	0.0	35.1	11.2	32.3	21.5	32.2
18	8.9	29.0	42.4	27.9	15.4	27.9
19	14.2	25.1	147.1	23.9	17.6	23.8
20	62.0	20.8	7.1	19.8	23.1	19.8
21	0.5	16.8	0.0	16.0	30.7	16.0
22	19.6	10.7	17.3	12.4	17.5	12.4
Total	545.6	510.0	830.8	546.6	542.7	547.5

Cotton was harvested using a spindle picker with a two-row header and a load cell used for obtaining seed cotton weights by plot. After cotton harvest, subsamples of seedcotton were ginned to collect seed samples and cottonseed was analyzed for total N content. Like leaf samples, seed samples were only collected for irrigation treatments 1, 5, 6, and 7. Nitrogen content in lint is minimal, so cottonseed N content can be considered the sole source of N removal by the cotton crop. Samples of seed cotton were ginned for turnout values and lint was sent to the USDA Agricultural Marketing Service's Memphis Classing Office for quality analysis. With turnout for each plot, a production yield in kg ha^{-1} was calculated. Turnout and seed N data were used to calculate N removal values in kg N ha^{-1} for each plot.

Preliminary analysis revealed a significant effect of year as well as interactions between year, irrigation, and soil type, therefore the 2 yr were analyzed separately. Mixed model analysis of variance was run in SAS 9.3 (SAS Institute, Cary, NC), and the experiment was analyzed as an RCBD split-plot. The experimental area was blocked on soil (random), irrigation was the whole plot treatment factor (fixed), and N source was the subplot treatment factor (fixed). For yield and quality data, all irrigation treatments were included in the analysis. When examining leaf N and N removal, the model was reduced to include only irrigation treatments 1, 5, 6, and 7, creating a smaller RCBD split-plot experiment. The block × irrigation × N source error term was tested in each year by Tukey's single degree of freedom test for interaction ($\alpha = 0.05$), which indicated that cotton yield responded to treatment combinations differently across blocks, as hypothesized (Tukey, 1949). This partial test allows the significance of an interaction to be tested when that interaction is actually the ANOVA error term. To address this interaction and strengthen the evaluation of yield response to treatment combinations across soils, a fixed effect "soil type" was added to the analysis. The variable "soil type" grouped blocks into low, intermediate, and high WHC based on soil data collected by Duncan (2012) and was validated by apparent groupings by yield response in the block × irrigation × N source interaction plots. This division was the same in both years, block 1 was low WHC, blocks 2 and 3 formed the intermediate WHC soil type, and blocks 4 to 7 formed the high WHC soil type. In each year, Levene's test for equality of variance reported an F statistic of less than 5, therefore, the pooled variance was used in mean separation. The low WHC soil type contained only one replication, however the results of Levene's test give us confidence that the error term from the other soil types is a good estimate for the error of the low WHC soil type. Mean separation for main effects and interactions was achieved using Fisher's LSD $p = 0.05$.

RESULTS AND DISCUSSION

Cotton Yields

This research was designed with an interest in the interaction between N source, irrigation regime, and soil type. Main treatment effects are reported, but may be of limited value when significant interactions occur. Nitrogen source had a significant main effect on lint yield in 2013 and 2014. In both years, AN resulted in higher yields, compared to ESN averaged across all soil blocks and all irrigation regimes (Table 3). Irrigation also had a significant main effect in both years (Table 4). However, cotton response to irrigation was dependent on soil type, so little emphasis should be placed on irrigation main effect. The effect of soil type on yield was examined to further validate separation of soil blocks into three soil types (Table 5). In both years, cotton yield decreased by soil type in a stepwise fashion,

Table 3. Effects of N source on lint yield, leaf N (early and late), and N removal.

N Source	df	Lint yield	Early leaf N	Late leaf N	N Removal
		kg ha^{-1}	—— % ——		kg ha^{-1}
		2013			
AN†		1634a‡	3.7a	2.7a	92a
ESN		1541b	3.6b	2.4b	84b
			ANOVA		
Source of variation					
N Source	1	***	**	***	**
N Source×Irr	6	**	ns	ns	ns
N Source×Soil	2	ns	ns	ns	ns
N Source×Irr×Soil	12	**	ns	ns	ns
		2014			
AN		1383a	3.5a	2.6a	70a
ESN		1239b	3.0b	2.4b	60b
			ANOVA		
Source of variation					
N Source	1	***	***	***	***
N Source×Irr	6	ns	ns	ns	ns
N Source×Soil	2	ns	ns	ns	ns
N Source×Irr×Soil	12	*	ns	ns	ns

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† AN, ammonium nitrate; ESN, Environmental Smart Nitrogen; Irr, irrigation.

‡ Within columns, means followed by the same letter are not significantly different according to LSD (0.05).

from high to low WHC soils. These results indicate grouping of soil blocks for an additional variable in analysis was justified and beneficial.

Significant irrigation × soil type interactions existed in 2013 and 2014 (Table 4). In both years, yields on high WHC soils were unaffected by irrigation treatment. Unexpectedly, we observed no yield decrease from the higher irrigation treatments in the high WHC soils, an effect others have observed (Gwathmey et al., 2011; Duncan, 2012). For intermediate WHC soils, significant yield loss was seen without irrigation or without enough irrigation in both years. In 2013, initiating irrigation at square and applying 25.4 mm wk^{-1} to total 85.9 mm yielded similarly to high WHC soils, while waiting until bloom to irrigate and applying 38.1 mm wk^{-1} to total 92.7 mm achieved optimal yields. In 2014, in intermediate WHC soils, irrigation beginning at bloom and applying 25.4 mm wk^{-1}, resulting in total application of 96.8 mm, was sufficient to achieve optimal yields. Irrigation regimes beginning earlier or applying more water did not result in further yield increase. For low WHC soils, large increases in yield were observed in both years with application of optimal irrigation. In 2013, applying 38.1 mm wk^{-1} starting at bloom was necessary to optimize yield, with total input of 92.7 mm, above which amount extra water was detrimental to yield. In 2014, the same treatment reached optimal yield, applying 145.3 mm. When irrigation was initiated at square with our highest rate of 38.1 mm wk^{-1},

Table 5. Effect of soil type, based on water holding capacity (WHC), on cotton lint yield.

Soil type	df	Lint yield
		kg ha^{-1}
	2013	
Low WHC		1246c†
Intermediate WHC		1637b
High WHC		1878a
		ANOVA
Sources of variation		
Soil type	2	***
	2014	
Low WHC		980c
Intermediate WHC		1387b
High WHC		1565a
		ANOVA
Sources of variation		
Soil type	2	***

*** Significant at the 0.001 probability level.

† Within columns, means followed by the same letter are not significantly different according to LSD (0.05).

Table 4. Main effect of irrigation treatment on cotton yield, and effect of irrigation depending on soil water holding capacity (WHC) on cotton yield. Irrigation treatments are ordered from least to highest amount of water applied.

Irrigation treatment				Lint yield, kg ha^{-1}			
					Irrigation × Soil type effect		
No.	Initiation, rate	Water applied	df	Irrigation main effect	Low WHC	Int. WHC	High WHC
		mm					
				2013			
7	Rainfed	0		1485bc†	1152cd	1392d	1911
3	Square, 12.7	43		1378c	730d	1455cd	1948
5	Bloom, 25.4	62		1517bc	1332bc	1389d	1833
2	Square, 25.4	86		1690b	1655ab	1626bcd	1789
4	Bloom, 38.1	93		1968a	1956a	2058a	1891
6	Sq. 12.7, Bl. 38.1	103		1514bc	836d	1807ab	1899
1	Square, 38.1	129		1558bc	1061cd	1735abc	1879
					ANOVA		
Source of variation							
Irrigation			6	***			
Irrigation × Soil			12			***	
				2014			
7	Rainfed	0		1054d	167d	1366abc	1627
3	Square, 12.7	64		1208cd	906bc	1166c	1551
5	Bloom, 25.4	97		1249c	752c	1565a	1431
2	Square, 25.4	128		1263c	742c	1422abc	1624
4	Bloom, 38.1	145		1500ab	1421a	1446abc	1634
6	Sq. 12.7, Bl. 38.1	161		1585a	1641a	1497ab	1616
1	Square, 38.1	191		1316bc	1234ab	1251bc	1465
					ANOVA		
Source of variation							
Irrigation			6	***			
Irrigation × Soil			12			***	

*** Significant at the 0.001 probability level.

† Within columns, means followed by the same letter are not significantly different according to LSD (0.05).

a significant yield downturn was seen. Although it seems contradictory that the year with higher total rainfall, 2014, would require more irrigation, this is due to prolonged dry periods between large rain events. These dry spells were enough to severely restrict non-irrigated yield in the low WHC soil. DeTar (2008) also highlighted a higher water requirement in coarse-textured soils, especially when exposed to prolonged dry spells, as was the case in 2014. Two wet years allowed irrigation to be withheld from low WHC soils until bloom, however, we would expect to need earlier irrigation on these soils in average to drier than average years, as shown by Duncan (2012).

Both 2013 and 2014 also saw significant three-way interactions between soil type, fertilizer, and irrigation (Fig. 1). Although AN significantly out-yielded ESN as a main effect, this three-way interaction reveals changing yield response to N source as soil WHC changed. In 2013, two of seven irrigation treatments responded with statistically higher yields when N source was AN in high and intermediate WHC soils, while the fertilizers yielded similarly in all other treatments. For low WHC soils, however, two of seven irrigation treatments responded with statistically higher yields when N source was ESN, while only one irrigation treatment yielded higher paired with AN. In 2014, four of seven irrigation treatments significantly favored high yields with AN in high WHC soils, two of seven favored high yields with AN in intermediate WHC soils, and in low WHC soils, only one irrigation treatment paired with AN resulted in significantly higher yield than with ESN. All other treatment combinations yielded similarly between N sources. These three-way interactions indicate more competitiveness of the ESN in low WHC soils than in deeper, higher WHC soils. However, this does not indicate a clear yield advantage achieved by using ESN in low WHC soils. Yields when using ESN were often similar to those achieved using AN, but AN more often outperformed ESN.

Several previous studies observed potato and corn fertilized with ESN to yield similarly with other N sources (Mozaffari et al., 2012a; Cahill et al., 2010; Wilson et al., 2009, 2010). However, both of these cropping systems require higher N input than cotton. Mozaffari et al. (2012b) observed similar yields in cotton fertilized with ESN and urea, when both sources were incorporated. In this study, ESN was not incorporated and compared with AN to evaluate its suitability for use in no-till cotton production.

Leaf Nitrogen Content, Nitrogen Removal, and Lint Quality

Nitrogen source was significant at both sampling times in both years (Table 3). Ammonium nitrate resulted in higher leaf N values compared to ESN at both sampling times in both years. Leaf N values were all within the reported sufficiency range at the first bloom sampling (3.0–4.5%). However, all leaf N values sampled mid-late bloom were under the reported

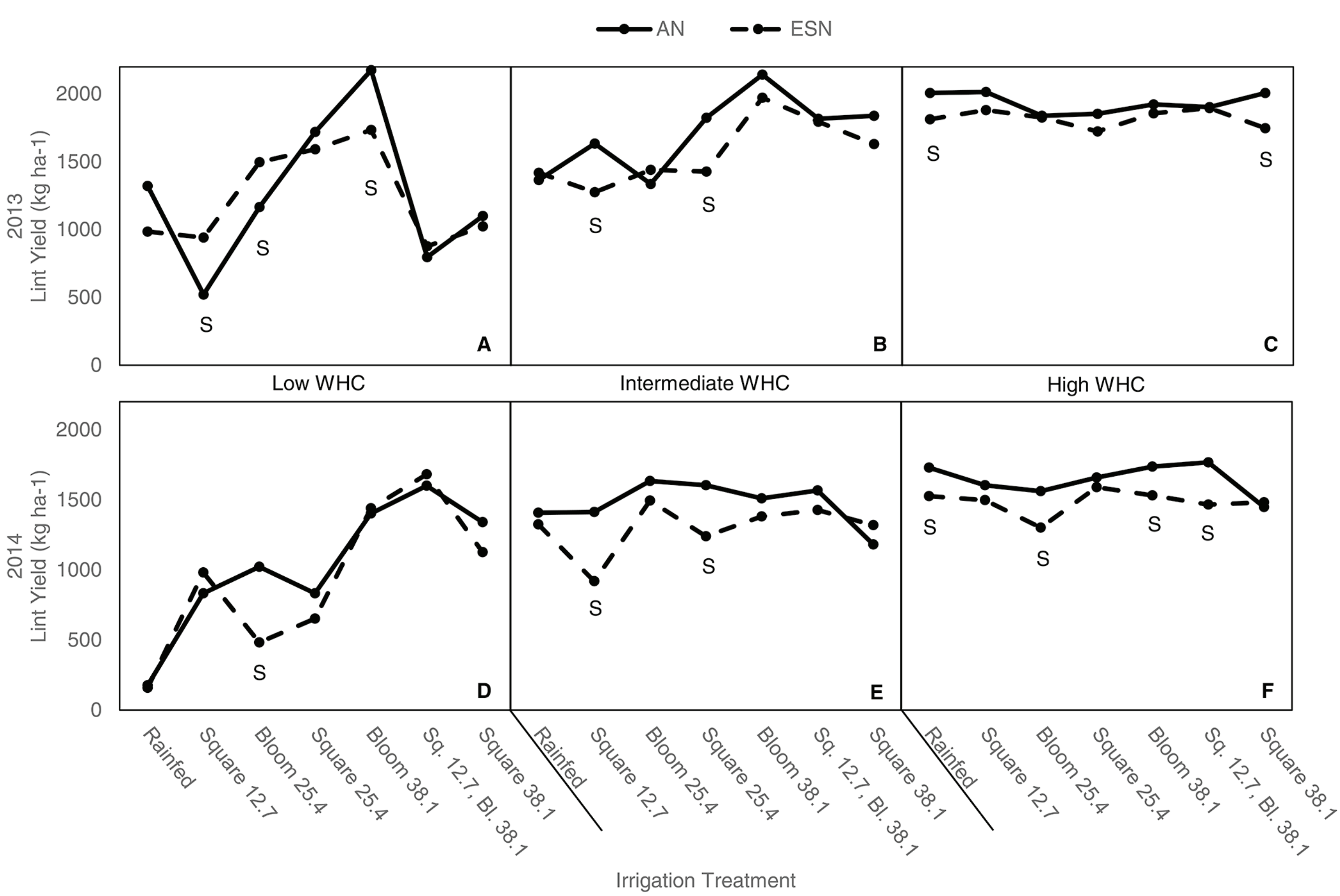

Fig. 1. Response of cotton lint yield to irrigation treatment and N source, depending on soil, in (A, B, C) 2013 and (D, E, F) 2014. Three soil types are delineated; (A, D) low water holding capacity (WHC), (B, E) intermediate WHC, and (C, F) high WHC. Irrigation treatments are arranged from least to greatest amount of water applied. Letter "S" denotes significant difference, LSD (0.05), between N sources within soil block and irrigation treatment.

sufficiency range (3.0–4.5%) (Campbell, 2000). Leaf N main effect of N source supports the notion of greater N availability in general from AN, which was indicated by a yield main effect reflecting higher yields with AN. Higher leaf N contents at first bloom presumably indicate uptake and storage of N that is soon transported to boll formation sites where it is actively used in seed production. Lower leaf N contents at the second sampling indicate a shift from vegetative growth toward a reproductive focus.

Nitrogen removal by the cotton crop via harvested seed was significantly affected by only N source (Table 3). Averaged across soil blocks and irrigation treatments, cotton fertilized with AN removed an average of 92.0 kg N ha^{-1} in 2013, while cotton fertilized with ESN removed 84.1 kg N ha^{-1}. In 2014, cotton receiving AN removed 70.4 kg N ha^{-1}, on average, while cotton receiving ESN removed 60.2 kg N ha^{-1}. The significant effect of N source on N removal again supports the notion of higher available N, on average, with AN compared to ESN, previously indicated by yields and leaf N content.

Lint quality components color grade, leaf grade, micronaire, length, strength, uniformity, and price were analyzed for main effects and interactions. No significant interactions existed for any quality components in either year. Several main treatment effects were significant. In 2013, N source had a significant effect on micronaire ($p = 0.0006$), with ESN having higher micronaire values. Length was also affected by N source ($p = 0.0451$), with AN resulting in higher length values. Irrigation treatment had a significant effect on micronaire ($p = 0.0194$), due to lower water application treatments giving lower micronaire values. These differences in quality components did not lead to any significant difference in lint price due to N source, irrigation treatment, or interaction of the two. In 2014, irrigation treatment had a significant effect on micronaire ($p = 0.0060$), dryland cotton having higher micronaire values than all irrigated treatments. No significant effects were detected on lint price due to N source, irrigation treatment, or interaction of the two.

Nitrogen Source Considerations

Concerning N source comparison, our results favor higher yields and N uptake/removal on average when using AN compared with ESN. While ESN did show more promise, in the form of either similar or sometimes higher yields than AN, in low WHC soils, it still was not observed to be a superior N source in that situation. Ammonium nitrate was used as the standard for comparison because there was little concern about ammonia volatilization loss when broadcast. Similar yields in many instances are encouraging for ESN effectiveness, but overall the effect of AN achieving higher yields, N uptake, and N removal begs the question of why ESN did not provide as much N availability.

The nature of polymer-coated urea is such that water must diffuse in and out of the coating to release N (Golden et al., 2011). When broadcast applied, the ESN granule surface area that is in contact with the soil is much less than it would be if incorporated. Less surface area in contact with soil could mean less opportunity for moisture diffusion. Being only in contact with the surface of soil also exposes the polymer-coated material to the first part of the soil profile to dry out, which could lead to less potential amount of time for water diffusion to occur. Being a urea-based fertilizer, there is also some concern about ammonia volatilization loss. While protected in polymer coating, urea should be stable, but a window of volatilization opportunity may exist as the urea solution is released (Golden et al., 2011). Another potential issue with broadcast ESN is physical movement of the fertilizer material. While a conventional granular material like AN will quickly dissolve into the soil profile, ESN prills remain on the soil surface even after N release has likely fully occurred. While no-till production systems leave crop residue on the surface, some movement of ESN with large rain events could occur. Movement of ESN within a plot or even off plot could lead to less N release than desired within the area of interest. Finally, when dealing with controlled release fertilizer material, it is necessary for release of N to match crop N demand for optimal performance (Gandeza et al., 1991). Our delayed broadcasting of ESN until post-emergence was within the allowable application window suggested by the manufacturer for cotton, but perhaps ESN could be applied at planting or even before planting and still provide ample available N at appropriate times and without exposing the N to potential leaching and ammonia volatilization loss early in the growing season. While ESN was generally outperformed by AN under conditions of this study, it was still a competitive N source, and warrants examination using different application strategies and timing. The ESN could be mixed with a more quickly available form of N to complement its slow release, or applied at an earlier time. The ESN also could be incorporated after application, although this may not be an option in most no-till or minimal tillage situations. We observed no interaction between N source and irrigation regime, so future research may be better served to evaluate more N sources, combinations of N source, or application timings across soils.

CONCLUSION

Cotton responded differently to irrigation, depending on soil type. High WHC soils did not respond to irrigation, positively or negatively, in either year. Intermediate WHC soils did require some supplemental irrigation to optimize yield, applying either 38.1 or 25.4 mm wk^{-1} starting at bloom, in 2013 and 2014, respectively. Low WHC soils saw the most dramatic yield increase from irrigating, when 38.1 mm wk^{-1} was applied starting at bloom. Low WHC soils also saw a decrease in yield with apparent over-irrigation. These 2 yr of data support previous irrigation work, which showed a need for a high rate of water input in low WHC soils, even in wet years, as well as the ability to leave high WHC soils non-irrigated without losing yield in a wet year. Overall, AN out-yielded ESN, however, N sources did respond somewhat differently between soil blocks. The ESN was more competitive with, even sometimes out-yielding AN, in low WHC soils. High and intermediate WHC soils favored higher yields when using AN over ESN. Leaf N samples and N removal values further supported the notion of higher available N from AN. The ESN may have suffered from being broadcast and unincorporated, as less surface area of the coating was available for diffusion. It also may be vulnerable to moving away from area of deposition, and to some volatilization. Finally, timing of N release from a controlled release fertilizer should match or precede N demand from the crop, and ESN may benefit from earlier application.

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