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Cotton Response to Variable Nitrogen Rate Fertigation through an Overhead Irrigation System

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Abstract

Recent increases in irrigated hectares in the Southeastern US have enabled growers to obtain higher yields through applying nutrients through irrigation water. Therefore, many growers apply nutrients through irrigation systems, known as fertigation. Currently, there are no practical decision-making tools available for variable-rate application of nitrogen (N) through overhead sprinkler irrigation systems. Therefore, field tests were conducted on cotton (*Gossypium hirsutum L.*) during the 2016 and 2017 growing seasons to 1) adapt the Clemson sensor-based N recommendation algorithms from a single side-dress application to multiple applications through an overhead irrigation system; and 2) to compare sensor-based VRFS with conventional nutrient management methods in terms of N use efficiency (NUE) and crop responses on three soil types. Two seasons of testing Clemson N prediction algorithms to apply multiple applications of N were very promising. The multiple applications of N compared to the grower's conventional methods (even though less N was applied) had no impact on yields in either growing season. There was no difference in cotton yields between 101 and 135 kg/ha N applications in either management zone. Also, there were no differences in yield between sensor-based, multiple N applications and conventional N management techniques. In relation to comparisons of the sensor methods only applying N in three or four applications, statistically increased yields compared to single or split applications in 2016. Applying N in four applications, statistically increased yields compared to single, split or triple applications in 2017. When the sensor-based methods were compared to the grower's conventional methods averaged over four treatments, the sensor-based N applications reduced fertilizer requirement by 69% in 2016 and 57% in 2017 compared to grower's conventional methods. When comparing N rates among the four sensor-based methods (three or four) applications, increased N rates by 22 kg/ha in 2016 and 26 kg/ha in 2017 compared to single or split applications but increased the cotton lint yields by 272 and 139 kg/ha, for 2016 and 2017, respectively.

Keywords

Cotton, Nitrogen, Fertility, Fertigation, Irrigation, Variable Rate, Sensor, Nutrient Management, Precision Agriculture, Normalized Difference Vegetation Index (NDVI)

1. Introduction

Irrigation can significantly increase crop yields and provide monetary savings compared to dryland production [1] [2]. Irrigated hectares have doubled from 1997 to 2011, and the adoption of irrigation has accelerated considerably since 2002, increasing at a rate of over 4000 hectares per year [3]. With the increases in irrigation across the Southeastern US, many growers apply nutrients through irrigation systems, known as fertigation, which has become a common practice for cotton growers in this region. Results of field research demonstrated the uptake of foliar applied ^{15}N urea by cotton leaves and translocation to the developing bolls [4]. Once the nitrogen (N) was applied, it was rapidly absorbed by the leaf at a rate of 30% within one hour and translocated to the closest boll within 6 to 48 hrs., after application. The remaining N is then moved progressively into adjoining bolls for the next few days with no translocation to other leaves [4].

In the Southeastern coastal plain region, cotton is commonly produced in fields with significant variation in soil texture, soil type, water holding capacity, and other factors, which have a major impact on crop N fertilizer management strategies [5]. In this region, yield response to N application also varies significantly among different sections of a production field, even in small fields (less than 4 hectares in size). This spatial variability adds significant challenges in managing N use and timing for a cropping season [6]. Most irrigation systems are setup to apply nutrients to crops by injecting them into the irrigation system. The most common fertigation is a uniform broadcasting application of N over the entire field which can be both costly and environmentally unsound.

Nitrates (NO_3^-) are one of two major essential plant N nutrients, but in excess amounts nitrate can cause significant water quality problems as an anion more vulnerable to leaching than the other major nitrogen form of ammonium (NH_4^+). The nitrate-N is also mobile in surface and ground water, and is a major source of water contamination, especially in the sandy soils of Southeastern coastal plain region. The current Environmental Protection Agency standard for nitrate-N for potable water supply is a maximum 10 mg·kg^{-1} [7]. Together with phosphorus, nitrate-N in excess can accelerate eutrophication causing dramatic increases in aquatic plant growth and changes in the composition of plants and animals that live in the stream [8]. Additionally, if each hectare were to have 22.67 kilograms less N fertilizers on 121,405 hectares, this would result in 6804 metric tons fewer N applied to the state's cotton fields. Using EPA 10 mg·kg^{-1} N limit, we would have 68 billion liters of N free drinking water in South Carolina.

On average, growers in the USA apply about 101 kg N/ha for cotton [3]. High production costs make it increasingly important for growers to reduce crop input costs while maximizing yields to stay competitive in the global market. For an example, a 20% reduction in N usage could save US growers over $1.8 billion annually [9]. Applying the proper rate of fertilizer for a crop is one of the major management decisions for producers in the Southeastern US.

To achieve the goal of N savings, Clemson University has developed cost-effective "sensor-based N application" systems for cotton, specifically for the coastal plain region [10] [11] [12] [13] [14]. Averaged over four years, the Clemson algorithm applied 47% less N without reducing cotton yields. These algorithms, which calculate side-dress N requirements based on an optical sensor, are specifically designed for Coastal Plain region to account for soil and crop variables characteristic of this region. These technologies are currently being transferred to South Carolina farmers through on-farm research and extension activities. Testing this technology on 13 grower's farms during 2015 to 2017 has shown that the sensor-based N management saved between $67 and $148 per hectare, by applying less N.

Currently, research is lacking on methods on timing and how much N to fertigate to cotton [15]. Using a sensor-based N calculator to apply multiple applications through an overhead irrigation system has the potential to reduce N applied to the crops. Additionally, it would decrease environmental impact associated with excess rates of N being used with a single application.

2. Objectives

The main goal of this project is to develop and test guidelines and recommendations for sensor-based and site-specific application of N fertilizer through overhead irrigation systems in cotton production. Specific project objectives were: 1) to adapt the Clemson University sensor-based N recommendation algorithm from single side-dress application to multiple applications through an overhead irrigation system; 2) To compare sensor-based and conventional N management methods in terms of nitrogen use efficiency (NUE) and crop responses on three soil types; 3) To create practical guidelines for N fertigation rates and frequency through an overhead irrigation system.

3. Methodology

3.1. Field Experiments

Field studies were conducted at the Clemson University's Edisto Research and

Education Center (34˚17'19.2"N, 79˚44'37.7"W) in 2016 and 2017. The soil present at the experimental sites was a Fuquay sand (loamy, kaolinitic, thermic, Arenic Plinthic Kandiudults) with a pH of 6.7 and an organic matter of 0.9% and a Varina loamy sand (fine, kaolinitic, thermic Plinthic Paleudults) with a pH of 6.6 and an organic matter of 1.6% in 2016 and 2017, respectively. A lateral move irrigation system was used to apply site specific fertigation to the experimental sites. A Veris 3100 soil electrical conductivity meter (Veris Technologies, Inc., Salina, KS, USA) was used to quantify the soil-texture variability of each experimental site. The experimental sites were then divided into two management zones (EC Zone 1 and EC Zone 2) based on the soil EC data and USDA soil texture map [12] [16].

The N source used during both growing seasons was a urea ammonium nitrate solution (UAN). UAN is a liquid fertilizer containing three forms of nitrogen: urea, ammonium-N and nitrate-N. The analysis for the solution used in these studies was 25% N and 3% S. The added sulfur is for plant amino acid synthesis which facilitates N uptake.

Treatment structure in these field studies were designed to adapt the Clemson sensor-based nitrogen recommendation algorithms from a single side-dress application to multiple applications through an overhead irrigation system. For this purpose, the following six N treatments were replicated seven times in plots of each management zones, using a randomized complete block design in 2016 and 2017:

1) Grower's method (135 kg N/ha, irrigated recommendation).
2) Grower's method (101 kg N/ha, dry land recommendation).
3) One N application based-on optical sensor data (NDVI).
4) Two N applications based-on optical sensor data (NDVI).
5) Three N applications based-on optical sensor data (NDVI).
6) Four N applications based-on optical sensor data (NDVI).

Plot dimensions were 7.8 m wide (96.5 cm row spacing) by 15.2 m long with 3 m alleys. Two Nitrogen Rich Strips (NRS) were created in the test field by applying a high N rate (168 kg/ha) such that N would not be limited throughout the optical sensing period during both growing seasons.

3.2. Equipment

A 76-m long linear move irrigation system (Reinke Manufacturing, Deshler, NE, USA), equipped with low energy precision application (LEPA) drops, was used to apply the variable-rate nitrogen (VRN) (**Figure 1**). The N injection system can control up to ten zones. Each zone was controlled independently to apply different N rates based on the prescription map. The pulsing system cycles individual (zone) or a group (zones) of N injection solenoids OFF and ON, to achieve desired N rates within the management zones. Each solenoid valve was attached to a manifold with four outlets which, injected N into four irrigation drop nozzles [17]. Therefore, each zone covered eight rows of cotton.

Figure 1. A 76-m linear move irrigation system used in these field studies [17].

The GreenSeeker® RT-200 mapping system (NTech Industries, Inc. Ukiha, CA, USA), mounted to a John Deere 6700 self-propelled sprayer (Deere & Company, Moline, IL, USA), was used during the 2016 and 2017 growing seasons to measure and quantify Normalized Difference Vegetation Index (NDVI) in cotton following the same methodology as described in Khalilian *et al.* 2017 [12]. The sensor readings were then used to calculate N requirements for the optical sensor based NDVI treatments (TRT 3-6).

Yield was obtained by weighing cotton harvested from each plot using a weighing apparatus installed on the cotton plot picker. The cotton pickers were setup for plot work and were calibrated daily before each harvest event. In the 2016 growing season, the middle four rows were harvested using a Case IH 1855 spindle picker modified for plots (CNH, Racine, WI, USA). In 2017 the middle four rows of each plot were harvested using a four row John Deere 9986 spindle picker modified for plots (Deere & Company, Moline, IL, USA).

3.3. Data Collection

During both growing seasons, before planting, composite soil samples were collected from each plot to determine pH and nutrient uniformity to ensure that other nutrients would not be limiting during the season. This was accomplished by randomly taking ten soil samples within each plot with a soil probe at a 15 cm depth, combining them into a bucket, and mixing them. After mixing, the samples were analyzed for pH, P, K, Ca, Mg, Zn, Mn, Cu, B, Na and cation exchange capacity (CEC) at the Clemson University Soil Testing Lab.

Biomass samples were collected for both growing seasons. To do this, 30 plants were harvested at the 18-node stage from each plot by cutting them flush with the ground using shears. The plants were taken to a field lab where the leaves, stems and bolls were separated and placed into a drier set on 80˚C for 48 hrs. After drying, the samples were removed and weighed.

Cotton leaf samples were collected from each plot for leaf N concentration. One week after final N fertigation application, 40 leaf and petiole samples were randomly collected from each plot. The leaf and petiole were separated from each other to ensure no nutrient movement between them occurred after removal from the plant. The samples were promptly taken to the Clemson University plant testing lab.

Plant height was measured by placing a tape measure on the soil and measuring to the terminal plant meristem. Thirty plants per plot were randomly measured for height during the 16-node stage by measuring from the soil to the plant's meristem. Cotton bolls were counted by randomly selecting 50 plants in each plot, counting the number of bolls per plant greater than 3-cm diameter. The total number of bolls counted per plot was then divided by 50 giving the average boll count.

4. Results and Discussion

In 2016, soil test results showed a potassium (K) deficiency in both EC zones. To correct this, 135 kg K/ha of potassium chloride (0-0-60) was applied to the entire field with a broadcast pull type spreader (Chandler Equipment Co., Gainesville, GA, USA) in March. This recommendation came from Clemson University Soil Testing Lab for irrigated cotton considering the current K soil test results. The 2017 soil test results showed adequate K for proper crop growth and were not suspected to be limiting throughout the growing season. During both growing seasons, soil test results also indicated that the test fields were very uniform in terms of pH and nutrients.

During the 2016 growing season there was no difference in cotton yields between 101 and 135 kg/ha grower conventional N applications methods (TRT 1 and 2). The experiment in 2016 was conducted in a field with only one soil type. Even though this field only had one soil type, the field was still divided into two management zones based on soil EC. Statistically, there was no difference in cotton yield between the two EC management zones, EC Zone 1 and EZ Zone 2 (**Table 1**). There were no differences in yield between sensor-based (TRT 5 and 6) and conventional N management techniques (TRT 1 and 2). Applying N in 3 or 4 applications (TRT 5 and 6), statistically increased yields compared to single or split sensor-based applications (TRT 3 and 4). The average cotton yields were 1165 and 1039 kg /ha, for 3 and 4 sensor-based applications and single or split sensor-based applications, respectively.

Averaged over 4 treatments, sensor-based N applications reduced fertilizer requirement by 69% compared to the grower's conventional practice for dry land cotton production (101 vs. 31 kg N/ha). Although multiple (3 or 4) applications increased N rates by 22 kg N/ha compared to one or two sensor-based applications but, increased the seed cotton yields by 272 kg/ha (**Table 1**).

Similar results were observed in 2017. Again, there was no difference in cotton yields between 101 and 135 kg/ha N applications in either management zone. Similar to 2016, the experimental site in 2017 had two management zones divided by soil EC and soil types. The soil EC correlated with the soil types that

Table 1. 2016 N totals (kg/ha) and cotton yield (kg/ha) from each EC zones. 1) 135 kg N/ha, 2) 101 kg N/ha, 3) One N application, 4) Two N applications, 5) Three N applications, 6) Four N applications. Treatments 3-6 N rates were based on NDVI.

Treatment No.	EC Zone 1		EC Zone 2	
	Yield (kg/ha)	Nitrogen Total (kg/ha)	Yield (kg/ha)	Nitrogen Total (kg/ha)
1	1207 a*	134.5 a	1140 a	134.5 a
2	1243 a	100.9 a	1174 a	100.9 a
3	1014 b	5.2 d	1064 b	24.2 c
4	1111 b	24.2 c	1101 b	32.8 c
5	1155 a	50.1 b	1279 a	46.7 b
6	1151 a	46.7 b	1221 a	41.5 b

*Values in the same column followed by the same letter are not significantly different at the 95% confidence level.

were observed on the USDA soil survey map for this field [16]. Applying N in 4 separate applications, statistically increased cotton yields compared to single, split, or three applications (Table 2).

The average cotton yields were 1293 and 1073 kg/ha, for the four and single applications, respectively. Averaged over 4 treatments, sensor-based N applications reduced N fertilizer requirement by 57% compared to grower's conventional method for dryland cotton production (101 vs. 43 kg N/ha) (Table 2). The reduction in N use would be even greater when compared to farmer's conventional method (135 vs. 43 kg N/ha) or 66% less N. Also, multiple (3 or 4) applications, increased N rates by 26 kg/ha compared to single or split applications but increased the cotton lint yields by 139 kg/ha (Table 2).

As the plants matured, differences in plant height could be observed. Plant height data were collected at the 18-node growth stage in 2016 and 2017. Applying multiple N applications and providing N only as it was needed, kept the plant height lower than in the grower's conventional practice (TRT 1 and 2) during both growing seasons. Statistically, there was no difference in plant height between sensor treatments. However, there was a significant difference between 135 and 101 kg N/ha treatments and sensor treatments. The results were the same for both growing seasons.

In 2016, the average sensor-based plant height for both management zones was 78 cm while the grower's conventional N treatment was 89 cm. The sensor treatments reduced plant height by 12%. For EC zone 1, there was a significant difference between grower's conventional practice and sensor-based treatments (Table 3). The average plant height for EC zone 1 was 77 cm for sensor treatments and 89 cm for grower's conventional practice. In EC zone 2, there was also a significant difference between grower practices and sensor-based treatments. The average plant height for EC zone 2 was 80 cm for sensor-based treatments (TRT 3-6) and 88 cm for grower's conventional practice (TRT 1-2) (Table 3).

Table 2. 2017 N totals (kg/ha) and cotton yield (kg/ha) for each EC zone. 1) 135 kg N/ha, 2) 101 kg N/ha, 3) One N application, 4) Two N applications, 5) Three N applications, 6) Four N applications. Treatments 3-6 N rates were based on NDVI.

Treatment No.	EC Zone 1		EC Zone 2	
	Yield (kg/ha)	Nitrogen Total (kg/ha)	Yield (kg/ha)	Nitrogen Total (kg/ha)
1	1429 a*	134.5 a	1408 a	134.5 a
2	1409 a	100.9 a	1397 a	100.9 a
3	1077 c	17.3 d	1239 b	31.1 c
4	1237 b	38.0 c	1262 b	44.9 c
5	1292 b	46.7 c	1317 b	46.7 c
6	1408 a	76.1 b	1401 a	74.3 b

*Values in the same column followed by the same letter are not significantly different at the 95% confidence level.

Table 3. 2016 Plant height (cm) for each EC zone. 1) 135 kg N/ha, 2) 101 kg N/ha, 3) One N application, 4) Two N applications, 5) Three N applications, 6) Four N applications. Treatments 3-6 N rates were based on NDVI.

Treatment No.	EC Zone 1	EC Zone 2
	Plant Height (cm)	Plant Height (cm)
1	90.1 a*	86.7 a
2	88.7 a	89.8 a
3	78.9 b	76.1 b
4	76.5 b	81.1 b
5	74.9 b	80.1 b
6	78.2 b	80.9 b

*Values in the same column followed by the same letter are not significantly different at the 95% confidence level.

In 2017, the average sensor-based plant height was 93 cm while the grower's conventional N practice treatment was 108 cm. Plant height was reduced by 13.6% in the sensor-based treatments. For EC zone 1, there was a significant difference between grower's conventional practice and sensor treatments (Table 4). The average plant height for EC zone 1 was 93 cm for sensor treatments (TRT 3-6) and 110 cm for grower's conventional practice (TRT 1-2). For EC zone 2, there was also a significant difference between grower's conventional practice and sensor treatments. The average plant height for EC zone 2 was 93 cm for sensor treatments (TRT 3-6) and 106 cm for grower's conventional practice (TRT 1-2) (Table 4).

For the sensor-based N applications, both treatments 3 and 4 had a lower yield than treatments 5 and 6. However, there was no difference in plant height between these two groups. This could be because N rates for treatments 3 and 4 were lower, allowing the plants to grow to the height comparable to that of

Table 4. 2017 Plant height (cm) for each EC zone. 1) 135 kg N/ha, 2) 101 kg N/ha, 3) One N application, 4) Two N applications, 5) Three N applications, 6) Four N applications. Treatments 3-6 N rates were based on NDVI.

Treatment No.	EC Zone 1	EC Zone 2
	Plant Height (cm)	Plant Height (cm)
1	108.1 a*	106.0 a
2	112.6 a	106.4 a
3	89.4 b	87.8 b
4	93.7 b	93.9 b
5	94.8 b	94.1 b
6	99.0 b	95.5 b

*Values in the same column followed by the same letter are not significantly different at the 95% confidence level.

treatments 5 and 6, but lacked the correct amount of N to produce equivalent yields, possibly reducing yield by way of square shedding. Plant heights in the grower's conventional practice treatments (TRT 1 and 2) were significantly taller due to the excess N that was applied to these treatments creating more vegetative growth and larger, harder to manage plants rather than additional yield (Table 4). This implies that applying N based on plants needs over multiple applications, can reduce plant size while maintaining yields and significantly reducing N use.

Boll counts were also collected during both growing season. During the 2016 growing season, statistically there was no difference in boll count between treatments 1, 2 and 6. Treatments 3, 4, and 5 produced fewer cotton bolls per plant. The average boll count for grower's conventional practice treatments were 12 harvestable bolls per plant and the average count for treatment 6 was 11 harvestable bolls per plant. The other three sensor treatments (TRT 3, 4, and 5) averaged 9 bolls per plant (Table 5).

During the 2017 growing season statistically, there was no difference in boll count between treatments 1, 2 and 6. However, the bolls per plant were significantly less in treatments 2, 3, 4, and 5. The average boll count for treatment 1 was 15 harvestable bolls per plant and the average count for treatment 6 was 15 harvestable bolls per plant. The other three sensor treatments (TRT 3, 4, and 5) averaged 12 bolls per plant and treatment 2 averaged 13 bolls (Table 5).

Both years followed similar trends; however, boll counts and yields were higher in 2017 compared to 2016. When analyzed by EC zone, there were statistical differences between zones in 2016. In EC zone 1, treatments 1, 2 and 6 were not statistically different. In EC zone 2, treatments 1, 2, 5 and 6 were not statistically different. For the 2017 growing season, EC zone 1 treatments 1 and 2 were not statistically different. In EC zone 2, treatments 1, 2, 5 and 6 were not statistically different.

Cotton biomass samples were not significantly different across treatments. This is surprising considering the differences in yield and plant height. Vegetative

Table 5. 2016 and 2017 boll count for each EC zone. 1) 135 kg N/ha, 2) 101 kg N/ha, 3) One N application, 4) Two N applications, 5) Three N applications, 6) Four N applications. Treatments 3-6 N rates were based on NDVI.

Treatment No.	2016		2017	
	Boll Count		Boll Count	
	EC Zone 1	EC Zone 2	EC Zone 1	EC Zone 2
1	13 a*	13 a	17 a	13 a
2	13 a	10 a	13 b	13 a
3	8 b	8 b	12 b	10 b
4	9 b	9 b	12 b	10 b
5	9 b	10 a	11 b	13 a
6	11 a	11 a	16 a	15 a

*Values in the same column followed by the same letter are not significantly different at the 95% confidence level.

growth could have made the plants weight more but not produce as many bolls needed for production by shedding them due to a lack of N or other environmental stresses. The average biomass for all treatments was 441 g and 593 g in 2016 and 2017, respectively. This was similar for plant height. Because plant heights of all the sensor treatments for both years were shorter, it seems counterintuitive that the biomasses were not statistically different. Again, this goes back to the potential for the plant investing resources into vegetative growth rather than focusing on fruit production as did the sensor treatments 5 and 6. Plants in sensor treatments 3 and 4 were the same height as the other sensor treatments; however, boll count and yield were lower. To elaborate on why the biomass was not statistically different because the plant may have had enough N to make the plant an acceptable size just when squaring started later in the season the plants were stressed and squares fell off lowering the yield and boll count. Cotton leaf samples were analyzed for leaf N concentration during both growing seasons. The samples were collected pre/post N applications in each plot. The pre-N leaf concentrations were not statistically different between all treatments ($P < 0.05$). The pre-N concentration testing was done to determine uniformity and check for any major nutrient deficiencies.

Correlations were observed between N rate and the leaf N concentration in a cotton leaf during the 2016 and 2017 growing season. Overall, the data showed an increase in leaf N concentration in cotton leaves as the soil applied N rate increased during both growing seasons. In 2016, leaf N concentrations were higher due to more soil available N left over from peanuts grown during the previous growing season. This was evident due to the leaf N concentration in leaves across all treatments was higher than data collected in 2017. Additionally, less sensor-based N was applied in 2016 in part due to the residual N in the soils due to the previous year of a leguminous crop fixing atmospheric N that would keep the NDVI numbers higher requiring less N be applied by the Clemson N algorithm. The R^2 value for the 2016 growing season was 0.9395 ($P < 0.05$) (**Figure 2**).

In 2017, the trend was similar to 2016 with increasing soil N rates applied. There was a correlation between leaf N concentrations found in the leaves (**Figure 3**). The R^2 value for the 2017 growing season was 0.8877 ($P < 0.05$).

In 2016, the grower's conventional practice treatments had a significantly greater N applied compared to the sensor treatments. There was also a significant difference between the leaf N concentration in both grower's conventional practice treatments and sensor-based treatments. However, this did not have any adverse effects related to yield in the sensor-based treatments 5 and 6 as yields were comparable to grower's conventional practice treatments in 2016. The leaf percent N concentration in grower's conventional practice was 3.9% for treatment 1 and 3.8% for treatment 2 compared to 3.3% for both sensor-based treatments 5 and 6.

In 2017, a similar trend continued with no adverse effects related to yield in the sensor-based treatment 6 as yields were comparable to grower's conventional practice treatment in 2017 even though there was a significantly lower N amount applied to the sensor-based treatments. The leaf percent N concentration in grower's conventional practice treatments was 3.5% for treatment 1 and 3.4% for treatment 2 compared to 3.1% for treatment 5 and 3.2% for treatment 6.

No difference in leaf percent N was found between EC zones in either year (**Table 6**). Since the applied N rates were low for all the sensor-based treatments. The N application amounts ranged from 14 to 40 kg/ha in 2016 and 22 to 38 kg/ha in 2017 grouping the sensor treatments together due to the N amounts applied were significantly less than that of the grower treatments.

5. Conclusions

Two seasons of testing showed promise for using the Clemson's N prediction algorithm to apply multiple applications of N. Multiple applications of N compared

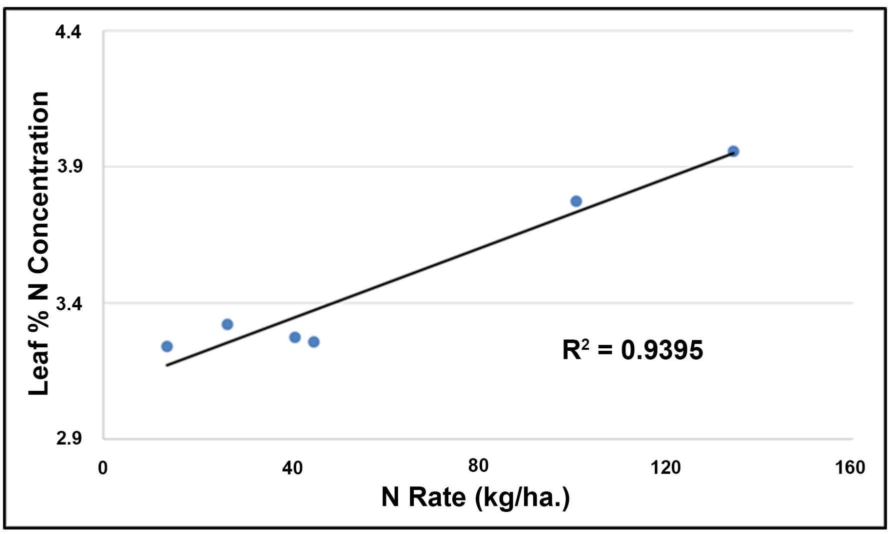

Figure 2. 2016 Leaf % N concentration vs. N rate.

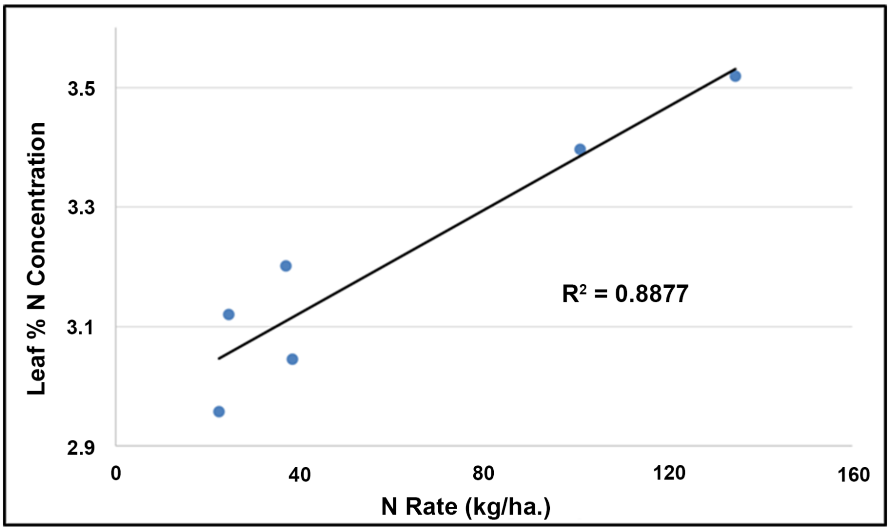

Figure 3. 2017 Leaf N % concentration vs. N rate.

Table 6. 2016 and 2017 cotton leaf N concentration from cotton taken in both EC zones after all N applications have been made. 1) 135 kg N/ha, 2) 101 kg N/ha, 3) One N application, 4) Two N applications, 5) Three N applications, 6) Four N applications. Treatments 3-6 N rates were based on NDVI.

Treatment No.	2016		2017	
	Leaf % N		Leaf % N	
	EC Zone 1	EC Zone 2	EC Zone 1	EC Zone 2
1	3.9 a*	4.0 a	3.7 a	4.0 a
2	4.0 a	3.6 a	3.8 a	3.6 a
3	3.2 b	3.2 b	3.1 b	3.2 b
4	3.3 b	3.4 b	3.1 b	3.4 b
5	3.2 b	3.3 b	3.3 b	3.3 b
6	3.3 b	3.3 b	3.4 b	3.3 b

*Values in the same column followed by the same letter are not significantly different at the 95% confidence level.

to the grower's conventional practices (even though much less N was applied) had no adverse impact on yields in either growing season. There was no difference in cotton yields between 101 and 135 kg/ha N grower's conventional N applications in either management zone. Also, there were no differences in yield between sensor-based, multiple N applications and conventional N management techniques.

The sensor-based methods (applying N in 3 or 4 applications) statistically increased yields compared to single or split applications in 2016. Applying N in 4 applications, statistically increased yields compared to single, split or triple applications in 2017.

When the sensor-based methods were compared to the grower's conventional practice methods averaged over four treatments, the sensor-based N applications reduced the fertilizer requirement by 69% in 2016 and 57% in 2017, compared to grower's conventional practices. When comparing N rates among the four sensor-based methods (3 or 4) applications, N rates increased by 22 kg/ha in 2016 and 26 kg/ha in 2017 compared to single or split applications but increased the cotton lint yields by 272 and 139 kg/ha in 2016 and 2017, respectively.

Plant height was significantly less in the sensor-based methods compared to the grower's conventional practice. This is beneficial since large plants could cause yield loss by shedding bolls, increased plant growth regulator use, disease, and harvest problems. Though sensor treatments were shorter plants yield was not affected. This is evident because there was no difference in yield between 101 and 135 kg N/ha treatments and three or four sensor-based applications treatments. This proves that applying N based on plants needs over multiple applications, can reduce plant size while maintaining yields and significantly reducing N use. During both growing seasons, statistically there was no difference in boll count between treatments 101 and 135 kg N/ha and four sensor-based applications. Cotton biomass samples were collected and were not significantly different from any of the treatments.

There was a positive correlation between the applied N rates and the leaf N concentration in cotton leaves. The R^2 values for the 2016 and 2017 growing seasons were 0.9395 and 0.8877, respectively. When more N was applied, the higher leaf N content was found in the plant's leaves. In 2016, the leaf N concentration for the 135 and 101 kg N/ha treatments was 3.9% and 3.8% compared to 3.3% for three and four sensor-based applications. In 2017 the leaf N concentration for the 135 and 101 kg N/ha treatments was 3.5% and 3.4% compared to 3.1% for three and 3.2% for four sensor-based treatments. However, these lower percent N levels had no impact on sensor-based treatment three and four cotton yields. The sensor-based methods applied significantly less N and cotton yields were similar or better than the conventional 135 and 101 kg N/ha rates.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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