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# AGRONOMY & SOILS

## Ability of Cotton (*Gossypium hirsutum* L.) to Recover from Early Season Nitrogen Deficiency

Emily Rutto, Brian D. Arnall*, Jerry L. May, Kay Butchee, and William R. Raun

### ABSTRACT

**Nitrogen (N) is important for cotton production but if poorly managed it can lead to reduced lint yield and low N use efficiency. This study was conducted to evaluate cotton's ability to recover from early season N deficiency and determine if a sensor-based N rate calculator (SBNRC) can be used to make mid-season N recommendations in cotton. The effect of sidedress N fertilizer (0, 33, 67, 101, and 134 kg N ha$^{-1}$) applied at early pinhead square (EPHS), first white flower (FWF), 30 d after first white flower (30 DAFWF), and four levels of preplant N (0, 33, 67, and 101 kg ha$^{-1}$), on cotton lint yield was investigated at two locations in Oklahoma. The results indicated that at 0 and 33 kg ha$^{-1}$ preplant N applications, cotton yield was significantly impacted by the timing of sidedress N. However, at Altus in 2009 and Lake Carl Blackwell (LCB) in 2010, cotton recovered from early season N deficiency and attained near maximum lint yield when sidedress N fertilizer was applied at EPHS or FWF. At Altus in 2010, cotton recovered when sidedress N was applied at EPHS and reduced when sidedress N was delayed until FWF. Yields were significantly (*P* < 0.05) reduced when application was delayed to 30 DAFWF at all sites. The results indicate normalized difference vegetative index (NDVI) could be used to make sidedress N recommendation for cotton at EPHS or FWF stage. This research validates the use of the SBNRC to improve in-season N recommendations in cotton production.**

Cotton (*Gossypium hirsutum* L.) has an indeterminate growth habit and can grow very tall especially when excess nitrogen (N) is applied. Growth regulators, such as mepiquat chloride, are generally applied to cotton to slow internode elongation (Stewart, 1986). This is an added cost to the producer and could be avoided with proper management of N fertilizer. In cotton production, N plays an important role stimulating the production of dry matter and energy rich compounds thereby regulating photosynthesis and cotton development. Studies have indicated that early N deficiency is associated with elevated levels of ethylene and leads to increased boll shedding if this is not corrected in time (Lege et al., 1997).

Research by Zhao and Oosterhuis (2000) found that insufficient N supply during cotton reproductive growth depressed leaf area, leaf net photosynthetic rate, and leaf chlorophyll content. Also, N deficiency increases total leaf nonstructural carbohydrate concentration leading to increased fruit abscission and decreased lint yield. These findings point out the need to timely correct N deficiencies in cotton if optimum yields are to be achieved. However, the questions are: will in-season N application salvage this crop even after going through earlier N deficiency stress, and up to what stage of cotton growth will that still be possible? Studies by Wright et al. (2003) have demonstrated that cotton can recover from slight N deficiencies. However, more research needs to be done to establish cotton recovery from more acute deficiencies.

The sensor-based N rate calculator (SBNRC) employs the use of remote sensing technology to allow for in-season application of N fertilizer. This technology assesses the crop N status by comparing plants grown under farmer's practice, to plants grown under conditions where N is not limiting (N rich reference). This technique of comparison is based on the principles established by Schepers et al. (1992a, b). Sensor-based technologies are employed to address both temporal and spatial variability (Raun et al., 2005, 2008). Guo (2005) described both the temporal and spatial variability found in lint yield. The study evaluated lint yield in eight fields over 3 yr. Lint yield from individual

E. Rutto, B.D. Arnall*, and W.R. Raun, Dept. of Plant and Soil Science, Oklahoma State University, Stillwater, OK 74078; J.L. May, Agronomy/Precision Department, OK Coop Grain 130 Main St., Kiowa, KS 67070; K. Butchee, Agriculture Dept., Western Oklahoma State College, Altus, OK 7352
Corresponding author: b.arnall@okstate.edu

fields, a measurement of spatial variability, ranged from 500 to 1400 kg ha$^{-1}$, whereas the range in mean averages of fields across years, a measure of temporal variability, went from 200 to 500 kg ha$^{-1}$.

Therefore, a technology that tries to establish a precise N fertilizer rate has to consider these facts to meet maximum crop yields. Past research has indicated that the variability present at 1 m$^2$ resolution can be detected using Green Seeker™ Hand Held Optical Sensor Unit (Trimble Industries Inc., Sunnyvale CA) sensors to obtain normalized difference vegetative index (NDVI). The NDVI is an index used to estimate green biomass (Tucker, 1979) and computed using the following formula:

$$NDVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}}$$

Where:

$\rho_{NIR}$ – Fraction of emitted NIR radiation returned from the sensed area (reflectance)

$\rho_{Red}$ – Fraction of emitted red radiation returned from the sensed area (reflectance).

Studies by Arnall (2008) showed that mid-season NDVI readings of cotton crop biomass can be used to estimate lint yields, and from that, the correct N rate the crop needs to achieve maximum yield. However, the evaluation of cotton's ability to recover from earlier season N deficiency and using the SBNRC to make mid-season N recommendations is yet to be fully explored.

We hypothesized that cotton deficiency at earlier growth stages can be detected using NDVI. Additionally, the N-deficient plants should recover when sidedress N is applied mid-season and produce maximum or near maximum yields. To test this hypothesis, field experiments were conducted at two locations in Oklahoma to evaluate the ability of cotton to recover from early season N deficiency and determine to what extent N application can be delayed and maximum yields still be achieved.

## MATERIALS AND METHODS

**Altus Research Station.** A field experiment was established at Altus in the southwest part of Oklahoma. The annual precipitation in this area from planting to harvesting was 57 and 61 mm for 2009 and 2010 cropping seasons respectively (Fig. 1). Within the same period, the air temperatures ranged from 2 to 28°C in 2009 and 5 to 29°C in 2010 (Fig. 1). The predominant soil profile in this study area was a Hollister clay loam (Fine, smectitic, thermic Typic Haplusterts), which consists of very deep, well drained, and very slowly permeable soils.

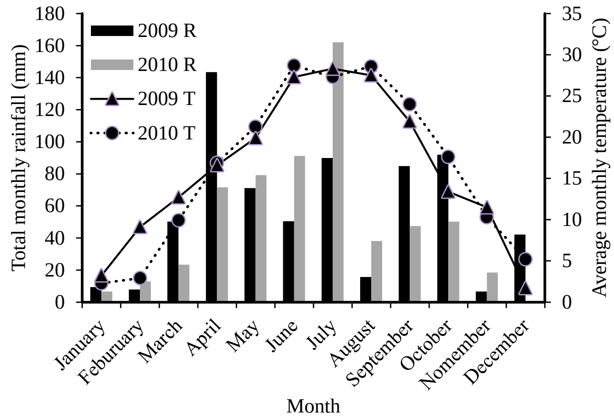


**Figure 1. Monthly rainfall and air temperature at Altus OK, 2009 and 2010. Note: R and T designate rainfall and temperature, respectively.**

**Lake Carl Blackwell Research Station.** Lake Carl Blackwell (LCB) is located in north central Oklahoma, 14 km west of Stillwater. From planting to harvesting, the annual rainfall for this location was 82 mm for both 2009 and 2010 cropping seasons (Fig. 2). The air temperature ranged from 0 to 27°C in 2009 and 3 to 28°C in 2010 between planting and harvesting (Fig. 2). The predominant soil types were a Port silt loam (Fine-silty, mixed, superactive, thermic Cumulic Haplustolls) and Oscar silt loam (Fine-silty, mixed, superactive, thermic Typic Natrustalfs) (USDA/NRCS soil taxonomy).

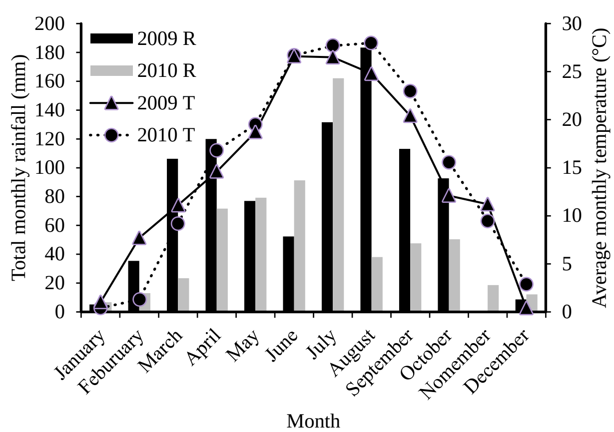


**Figure 2. Total monthly rainfall and average air temperature at Lake Carl Blackwell OK, 2009 and 2010. Note: R and T designate rainfall and temperature, respectively.**

**Treatments and Data Collection.** Soils samples (0-15 cm) from each site were collected and analyzed before treatments were applied (Table 1). Soil was sieved through a 2-mm screen before analysis. Soil pH was determined by adding 15 ml of water into 15 g of soil, shaken well, and left to equilibrate for 1 hr. The reading was then taken using a pH meter. Nitrate N was determined by adding 25 ml of calcium sulfate in 10 g of soil. The suspension was then shaken for 30 min, filtered, and analyzed on a flow injection analyzer using cadmium reduction chemistry. Total combustible N and carbon was determined using a dry combustion LECO analyzer. The available potassium (K) and phosphorus (P) were analyzed by adding 20 ml Mehlich 3 into 2 g of soil, shaken for 5 min, filtered, and analyzed by inductively coupled plasma (ICP) emission spectrometry.

At each location, a field experiment with three replications in a randomized complete block design was established. Individual plot size was 4 rows wide and 6 m long, with a row spacing of 75 cm at LCB and 100 cm at Altus. Three preplant-only treatments of 0, 67, and 134 kg N $ha^{-1}$ (Treatments 1, 2, and 3) were established (Table 2). Treatment 3 (134 kg N $ha^{-1}$) was recommended yield goal N rate and considered typical practice. To determine the ability of cotton to recover from earlier N deficiency, a factorial combination of N application schemes and sidedress N application timings were established (Table 2). Four preplant N rates (0, 34, 67, 101 kg N $ha^{-1}$) to simulate different levels of N deficiency were used.

**Table 1. Soil chemical properties determined from initial soil samples (0-15 cm) at two locations in Oklahoma.**

| Site | Year | pH | Total combustible N | Total C | $NO_3$-N | P | K |
|---|---|---|---|---|---|---|---|
| | | | g $kg^{-1}$ | | | mg $kg^{-1}$ | |
| Altus | 2009 | 8.0 | NA[z] | 8 | 5 | 16 | 280 |
| LCB[y] | 2009 | 5.9 | 1.0 | 3.2 | 11 | 22 | 138 |
| Altus | 2010 | 8.2 | 0.4 | 10 | 10 | 29 | 282 |
| LCB[y] | 2010 | 6.5 | 0.8 | 3.8 | 15 | 10 | 101 |

[z] Data was not determined

[y] Lake Carl Blackwell

**Table 2. Treatments used in the trials conducted at Altus and Lake Carl Blackwell, Oklahoma, 2009-2010.**

| Treatment | Preplant[z] N Rate (kg $ha^{-1}$) | Sidedress[y] N Rate (kg $ha^{-1}$) | Sidedress[y] Growth Stage of Application |
|---|---|---|---|
| 1 | 0 | 0 | - |
| 2 | 67 | 0 | - |
| 3 | 134 | 0 | - |
| 4 | 0 | 134 | Early pinhead square |
| 5 | 0 | 134 | White flower |
| 6 | 0 | 134 | 30 d after white flower |
| 7 | 34 | 101 | Early pinhead square |
| 8 | 34 | 101 | White flower |
| 9 | 34 | 101 | 30 d after white flower |
| 10 | 67 | 67 | Early pinhead square |
| 11 | 67 | 67 | White flower |
| 12 | 67 | 67 | 30 d after white flower |
| 13 | 101 | 34 | Early pinhead square |
| 14 | 101 | 34 | White flower |
| 15 | 101 | 34 | 30 d after white flower |

[z] Preplant N was applied as UAN (28-0-0) at Lake Carl Blackwell and Urea (46-0-0) at Altus.

[y] Sidedress N applied as UAN (28-0-0) at both sites

Sidedress N at 34, 67,101, and 134 kg N $ha^{-1}$ application rate were applied at early pinhead square (50% of plants in field have the first pinhead squares) (EPHS), first white flower (50% of plants have the first flower) (FWF), and 30 d after first white flower (30 DAFWF). Details of preplant and sidedress N combinations used are shown in Table 2. At LCB, preplant was applied as 28-0-0 liquid UAN with a sprayer using T-Jet Streamer nozzle, whereas at Altus, preplant was applied as urea (46-0-0). Sidedress N was applied at both locations as liquid UAN (28-0-0) along the base of each cotton row using 50-ml and 200-ml syringes. More details on planting, herbicide and insecticide applications, sensing, and harvesting for each experiment are described in Tables 3 and 4 for Altus and Tables 5 and 6 for LCB.

The two center rows were sensed at EPHS, FWF, and 30 DAFWF using a hand-operated Green Seeker TM active sensor before every sidedress N application. The sensor was held 0.8 m above the cotton canopy and all readings taken during the day. For both seasons, trials at Altus received a harvest aid chemical application in October (Tables 3 and 4), whereas at LCB, the harvest aid chemical application was made in September (Table 5) each year. At maturity, the two center rows of each plot were harvested with a stripper at Altus (both seasons) and LCB (2010). Due to unavailability of a mechanical harvester, cotton was hand-harvested at LCB in 2009. Seed cotton was manually pulled from the bolls and any foreign material was removed. Seed cotton was then weighed and a 500-g sample was collected and ginned to calculate lint ratio. Lint weights per plot were obtained by multiplying the seed cotton yield by lint ratio.

**Table 3. Field trial information for Altus, OK in 2009.**

| Date | Action | Description |
|---|---|---|
| 28 March | Pre-emergence Herbicide | Trifluralin HF(2,6-dinitro-N,N-dipropyl-4-trifluromethyl) @ 2.4 L $ha^{-1}$ |
| 03 May | Planting | Deltapine DP 0924 B 2RF @175,00 seeds $ha^{-1}$ |
| 03 May | Insecticide | Temik 15G (Aldicarb) @ 0.6 kg ai $ha^{-1}$ in furrow at planting |
| 05 June | Post- emergence Herbicide, Aerial | Staple LX(2-chloro-6-[(4,6-dimethoxy-2-pyrimidinyl)thio] benzoic) acid@ 0.26 L $ha^{-1}$; Mad Dog Plus (Glyphosate) 0.47 L $ha^{-1}$; Vydate C-LV ([Methyl N'N'-dimethyl-N-[(methylcarbamoyl) oxy]-1-thiooxamimidate ) @ 0.47 L $ha^{-1}$; Choice Weather Master (Aqueous mixture of salts) @3.5 L $ha^{-1}$; Activator 90 nonionic surfactant @0.5% v/v. |
| 05 June | Insecticide | Vydate C- LV([Methyl N'N'-dimethyl-N-[(methylcarbamoyl) oxy]-1-thiooxamimidate) @ 0.47 L $ha^{-1}$. |
| 02 July | EPHS$^z$ Sensing/ Sidedress | - |
| 12 July | Herbicide, Aerial | Mad Dog Plus (Glyphosate) @ 3.5 L $ha^{-1}$; Activator 90 nonionic surfactant @0.5% v/v. |
| 20 July | FWF$^y$ Sensing/ Sidedress | - |
| 19 August | 30DAFWF$^x$ Sensing/ Sidedress | - |
| 02 October | Harvest Aid | Finish 6 Pro (Ethephon, Cyclanilide) @ 1.7 L $ha^{-1}$; Ginstar EC (N-pheny-N'-(1,2,3-thiadiazol-5'yl)-urea; 3-(3,4-dichlorophenyl)-1,1-dimethylurea@ 1.4 L $ha^{-1}$; Activator 90 nonionic surfactant @0.5 % v/v |
| 11 October | Harvest Aid | Boll Buster (Ethephon 2-Chlorethyl)phosphonic acid) @ 1.2 L $ha^{-1}$; ET Herbicide/Defoliant ( Ethyl 2-chloro-5-(4-chloro-5-difluoromethoxy-1-methyl-pyrazol-3-yl)-4-fluorophenoxyacetate) @ 0.14 L $ha^{-1}$; Herbimax Petroleum oil (petroleum hydrocarbons plus surfactant) @ 1.4 L $ha^{-1}$ |
| 11 December | Harvest | Two middle rows at 2 rows x 6 m /plot with a stripper |

$^z$ **Early pinhead square**

$^y$ **First white flower**

$^x$ **30 d after first white flower**

**N.B: Chemical names for all the chemicals used in the trial are indicated in brackets.**

**Table 4. Field trial information for Altus, OK in 2010.**

| Date | Action | Description |
|---|---|---|
| 30 March | Pre-emergence Herbicide | Trifluralin HF(2,6-dinitro-N,N-dipropyl-4-trifluromethyl) @ 2.4 L $ha^{-1}$ |
| 05 May | Planting | Deltapine DP 0924 B 2RF @175,00 seeds $ha^{-1}$ |
| 05 May | Insecticide | Temik 15G (Aldicarb) @ 0.6 kg ai $ha^{-1}$ in furrow at planting |
| 09 June | Post-emergence Herbicide, Aerial | Staple LX(2-chloro-6-[(4,6-dimethoxy-2-pyrimidinyl)thio] benzoic) acid@ 0.26 L $ha^{-1}$; Mad Dog Plus (Glyphosate) 0.47 L $ha^{-1}$; Vydate C-LV ([Methyl N'N'-dimethyl-N-[(methylcarbamoyl) oxy]-1-thiooxamimidate ) @ 0.47 L $ha^{-1}$; Choice Weather Master (Aqueous mixture of salts) @3.5 L $ha^{-1}$; Activator 90 nonionic surfactant @0.5% v/v. |
| 09 June | Insecticide | Vydate C- LV([Methyl N'N'-dimethyl-N-[(methylcarbamoyl) oxy]-1-thiooxamimidate) @ 0.47 L $ha^{-1}$. |
| 09 July | EPHS[z] Sensing/ Sidedress | - |
| 12 July | Herbicide, Aerial | Mad Dog Plus (Glyphosate) @ 3.5 L $ha^{-1}$; Activator 90 nonionic surfactant @0.5% v/v. |
| 19 July | FWF[y] Sensing/ Sidedress | - |
| 13 August | 30DAFWF[x] Sensing/ Sidedress | - |
| 02 October | Harvest Aid | Finish 6 Pro (Ethephon, Cyclanilide) @ 1.7 L $ha^{-1}$; Ginstar EC (N-pheny-N'-(1,2,3-thiadiazol-5'yl)-urea; 3-(3,4-dichlorophenyl)-1,1-dimethylurea@ 1.4 L $ha^{-1}$; Activator 90 nonionic surfactant @0.5 % v/v |
| 14 October | Harvest Aid | Boll Buster (Ethephon 2-Chlorethyl)phosphonic acid) @ 1.2 L $ha^{-1}$; ET Herbicide/Defoliant ( Ethyl 2-chloro-5-(4-chloro-5-difluoromethoxy-1-methyl-pyrazol-3-yl)-4-fluorophenoxyacetate) @ 0.14 L $ha^{-1}$; Herbimax Petroleum oil (petroleum hydrocarbons plus surfactant) @ 1.4 L $ha^{-1}$ |
| 11 December | Harvest | Two middle rows at 2 rows x 6 m /plot with a stripper. |

[z] Early pinhead square

[y] First white flower

[x] 30 d after first white flower

N.B: Chemical names for all the chemicals used in the trial are indicated in brackets.

**Table 5. Field trial information for Lake Carl Blackwell, OK in 2009.**

| Date | Action | Description |
|---|---|---|
| 27 May | Planting | Deltapine 0924 B2RF @ 128,494 seeds $ha^{-1}$ |
| 13 June | EPHS[z]Sensing/ Sidedress | - |
| 15 June | Herbicide | Glyphosate(N-(phosphonomethyl)glycine) @ 4.7 L $ha^{-1}$ |
| 13 July | FWF[y] Sensing/ Sidedress | - |
| 12 August | 30DAFWF[x] Sensing/ Sidedress | - |
| 25 September | Harvest Aid | Def(S,S,S-Tributyl phosphorotrithioate) @ 1.2 L $ha^{-1}$; Dropp (Thidiazuron)@ 1.5 L $ha^{-1}$; Finish (Ethephone, Cyclanilide) @9.3L $ha^{-1}$ |
| 13 December | Harvest | Middle 2 rows x 6 m per plot, by hand |

[z] Early pinhead square

[y] First white flower

[x] 30 d after first white flower

N.B: Chemical names for all the chemicals used in the trial are indicated in brackets.

**Table 6. Field trial information for Lake Carl Blackwell, OK 2010.**

| Date | Action | Description |
|---|---|---|
| 25 May | Planting | DynaGrow 995-2 B2RF at 129,167 seeds ha$^{-1}$ |
| 07 June | EPH[z] Sensing/ Sidedress | - |
| 17 June | Herbicide | Glyphosate(N-(phosphonomethyl- glycine) @ 4.7 L ha$^{-1}$ |
| 27 July | FWF[y] Sensing/ Sidedress | - |
| 28 July | Insecticide application | Warrior (Lambda Cylothrin) @ 0.2 ml ha$^{-1}$ |
| 25 August | 30DAFWF[x] Sensing/ Sidedress | - |
| 28 September | Harvest Aid | Def(S,S,S-Tributyl phosphorotrithioate) @ 1.2 L ha$^{-1}$; Dropp (Thidiazuron)@ 1.5 L ha$^{-1}$; Finish (Ethephone, Cyclanilide) @9.3L ha$^{-1}$ |
| 13 December | Harvest | Middle 2 rows x 6 m per plot , by hand |

[z] Early pinhead square

[y] First white flower

[x] 30 d after first white flower

**Data Analysis.** Treatment effect on lint yield and NDVI was determined by statistically analyzing the data using SAS (SAS Institute, 2003). The general linear model procedure was used and means were separated using protected LSD. The relationship between NDVI and preplant N was determined by plotting regression graphs using treatment means. The PROC REG procedure in SAS was used to determine parameter estimates and test if the slope of the regression line was equal or greater than zero ($H_O$: $\beta = 0$ or $H_1$: $\beta > 0$).

## RESULTS

**In-Season NDVI.** Initial cotton response to applied preplant N was determined by measuring NDVI at EPHS, FWF, and 30 DAFWF from the plots prior to receiving sidedress N. Plots that had been fertilized at a prior stage where not included. Generally, NDVI values taken at EPHS were low across seasons and years due to low crop biomass at that stage. Additionally, with the exception of Altus in 2010, low $R^2$ values were generally recorded for NDVI taken at EPHS, and the slopes of the regression line were not significantly ($P > 0.05$) different from zero (Table 7 and 8).

At Altus in 2009, NDVI did not differ with preplant N rate at EPHS (Fig. 3). However, NDVI values taken at FWF and 30 DAFWF increased by 0.02 and 0.03 respectively with each kilogram increase in preplant N applied (Fig. 3). Preplant N application explained 35% and 51% of NDVI increase for NDVI taken at FWF and 30 DAFWF respectively (Table 7). Compared to treatments that received 33, 67, and 101 kg N ha$^{-1}$ preplant, treatments with 0 kg N ha$^{-1}$ preplant recorded low NDVI and yellowing of the crop at FWF and 30 DAFWF; an indication that cotton suffered some N deficiency (Fig. 3). In 2010, NDVI values taken at EPHS and 30 DAFWF responded poorly to preplant N application, although there was slight increase in NDVI with each increase in preplant N rate (Fig. 4). The NDVI values taken at FWF showed a significant ($P < 0.001$) linear increase with preplant N rate (Fig. 4) with 68% of that increase explained by preplant N application (Table 7). Plots with no preplant N recorded low NDVI at FWF indicating some level of N deficiency. At FWF and 30 DAFWF, NDVI remained fairly constant beyond 101 kg N ha$^{-1}$ sidedress N. This implied that NDVI did not increase (reached saturation limit) even with further increased N rate (Fig. 4).

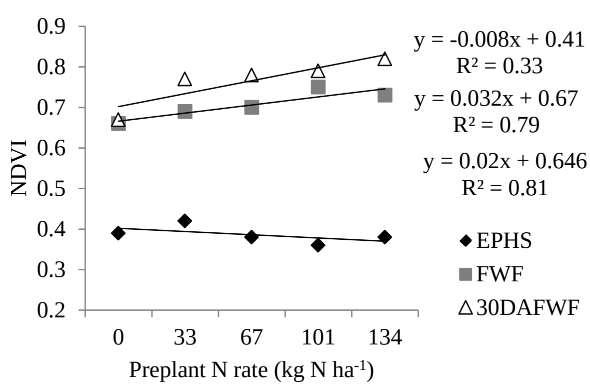


**Figure 3. Effect of preplant N application on normalized difference vegetative index (NDVI) at early pinhead (EPHS), first white flower (WF), and 30 d after first white flower (30 DAFWF) cotton growth stages in 2009, Altus, OK. Note: The regression equations corresponds to the legend from top to bottom.**

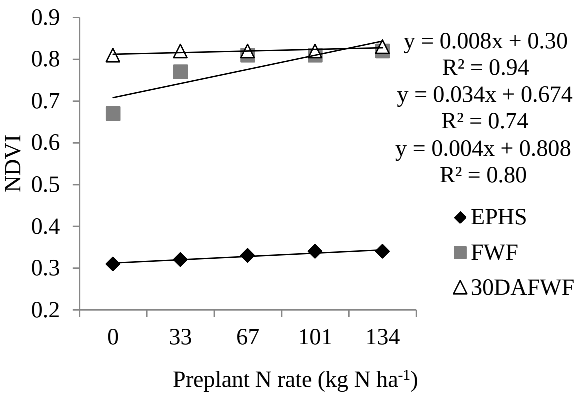


**Figure 4. Effect of preplant N application at on normalized difference vegetative index (NDVI) at early pinhead (EPHS), first white flower (WF), and 30 d after first white flower (30 DAFWF) cotton growth stages in 2010, Altus, OK. Note: The regression equations corresponds to the legend from top to bottom.**

At LCB in 2009, there were no significant ($P < 0.05$) differences in NDVI due to preplant N application at any of the growth stages (Fig. 5). The slope of the regression line was not significantly ($P > 0.05$) greater than zero implying that there was no relationship between preplant N and NDVI (Table 8). In 2010, NDVI at EPHS, FWF, and 30 DAFWF increased with preplant N rate but the trend was inconsistent (Fig. 6). Application of preplant N explained 19%, 32%, and 21% of the increase in NDVI taken at EPHS, FWF, and 30 DAFWF respectively (Table 8). The NDVI values from plots that received low preplant N rate (0 and 33 kg N ha$^{-1}$) were low for all the growth stages compared to those that received between 67 and 134 kg N ha$^{-1}$ (Fig. 6). This indicated that with 0 or 33 kg N ha$^{-1}$ preplant, N in the soil was inadequate for the crop growth.

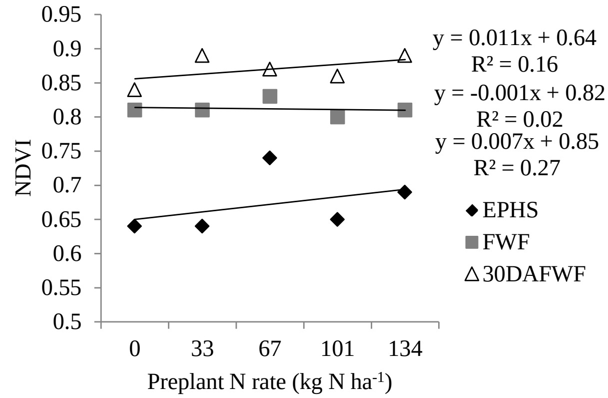


**Figure 5. Effect of preplant N application on normalized difference vegetative index (NDVI) at early pinhead (EPHS), first white flower (WF), and 30 d after first white flower (30 DAFWF) cotton growth stages in 2009, Lake Carl Blackwell, OK. Note: The regression equations corresponds to the legend from top to bottom.**

**Table 7. Regression analysis to test $H_O$: $\beta = 0$ or $H_1$: $\beta > 0$ for normalized difference vegetative index taken at early pinhead square (EPHS), first white flower (FWF), and 30 d after first white flower (30 DAFWF) in 2009 and 2010 at Altus, OK.**

| Source of Variation | Mean Squares | | | | | |
|---|---|---|---|---|---|---|
| | | 2009 | | | 2010 | |
| | EPHS | FWF | 30 DAFWF | EPHS | FWF | 30 DAFWF |
| Model | 0.002 | 0.01** | 0.03*** | 0.002† | 0.03*** | 0.0007 |
| Error | 0.003 | 0.002 | 0.002 | 0.0006 | 0.001 | 0.0004 |
| $R^2$ | 0.05 | 0.35 | 0.51 | 0.21 | 0.68 | 0.13 |
| Parameter Estimate | Slope | | | | | |
| Preplant N | ns | ** | ** | † | *** | ns |

**, ***, † significant at the 0.01, 0.001, and 0.1 probability levels, respectively.

ns, not significant at $P > 0.05$

**Table 8. Regression analysis to test $H_O$: $\beta = 0$ or $H_1$: $\beta > 0$ for normalized difference vegetative index taken at early pinhead square (EPHS), first white flower (FWF), and 30 d after first white flower (30 DAFWF) in 2009 and 2010 at Lake Carl Blackwell, OK.**

| Source of Variation | Mean Squares | | | | | |
|---|---|---|---|---|---|---|
| | | 2009 | | | 2010 | |
| | EPHS | FWF | 30 DAFWF | EPHS | FWF | 30 DAFWF |
| Model | 0.0007 | 0.0004 | 0.0008 | 0.02 | 0.03** | 0.008† |
| Error | 0.02 | 0.001 | 0.0004 | 0.008 | 0.004 | 0.002 |
| $R^2$ | 0.0032 | 0.025 | 0.16 | 0.19 | 0.32 | 0.21 |
| Parameter Estimate | Slope | | | | | |
| Preplant N | ns | ns | ns | ns | ** | † |

**, † significant at the 0.01, and 0.1 probability levels, respectively.

ns, not significant at $P > 0.05$

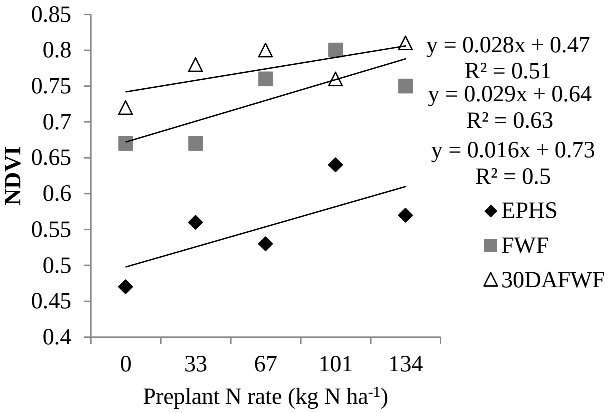


**Figure 6. Effect of preplant N application on normalized difference vegetative index (NDVI) at early pinhead (EPHS), first white flower (WF), and 30 d after first white flower (30 DAFWF) cotton growth stages in 2010, Lake Carl Blackwell, OK. Note: The regression equations corresponds to the legend from top to bottom.**

**Yield Recovery.** In 2009 at Altus, lint yields increased with increased preplant N application (Table 9). Sidedress N, growth stage, and interaction between the two factors contributed to a significant increase in lint yields at $P < 0.05$, $P < 0.0001$, and $P < 0.001$ probabilities respectively (Table 10). Treatments 2 through 15 resulted in higher lint yields compared to that of the control and ranged from 744 to 1604 kg ha$^{-1}$. Unexpectedly, with exception of Treatment 6, the lint yields from the rest of the factorial combinations did not significantly ($P > 0.05$) differ from that of the N-rich plot (Treatment 3). Application of 0 and 33 kg N ha$^{-1}$ preplant, followed by sidedress N by FWF, contributed to cotton's recovery from earlier N deficiency and attained high lint yields. Lint yields declined when sidedress N was applied 30 DAFWF. Treatments that received 67 or 101 kg N ha$^{-1}$ preplant, had high lint yields when sidedress N was applied at EPHS or FWF, but not significantly ($P > 0.05$) different from lint yields obtained from treatments which sidedress N was applied 30 DAFWF (Table 9).

**Table 9. Means for lint yield as affected by split N application applied preplant and sidedress at early pin head square, first white flower, and 30 d after first white flower, 2009 and 2010, Altus and Lake Carl Blackwell (LCB), OK.**

| TRT$^{z}$ | Preplant (kg N ha$^{-1}$) | Sidedress (kg N ha$^{-1}$) | Application time | Lint yields (kg ha$^{-1}$) 2009 | | 2010 | |
|---|---|---|---|---|---|---|---|
| | | | | Altus | LCB$^{y}$ | Altus | LCB$^{y}$ |
| 1 | 0 | 0 | Planting | 744$^{fx}$ | 841$^{ba}$ | 829$^{g}$ | 1381$^{b}$ |
| 2 | 67 | 0 | Planting | 1317$^{cde}$ | 773$^{ba}$ | 1378$^{ef}$ | 1531$^{ab}$ |
| 3 | 134 | 0 | Planting | 1546$^{ab}$ | 657$^{b}$ | 1785$^{bcd}$ | 1751$^{ab}$ |
| 4 | 0 | 134 | EPHS$^{w}$ | 1572$^{a}$ | 832$^{ba}$ | 1957$^{ab}$ | 1788$^{ab}$ |
| 5 | 0 | 134 | FWF$^{v}$ | 1449$^{abcd}$ | 834$^{ba}$ | 1320$^{f}$ | 1697$^{ab}$ |
| 6 | 0 | 134 | 30 DAFWF$^{u}$ | 857$^{f}$ | 902$^{ba}$ | 1460$^{def}$ | 1337$^{b}$ |
| 7 | 33 | 101 | EPHS | 1583$^{a}$ | 772$^{ba}$ | 1918$^{abc}$ | 1601$^{ab}$ |
| 8 | 33 | 101 | FWF | 1604$^{a}$ | 767$^{ba}$ | 1619$^{bcdef}$ | 1633$^{ab}$ |
| 9 | 33 | 101 | 30 DAFWF | 1148$^{e}$ | 795$^{ba}$ | 1565$^{dcef}$ | 1466$^{b}$ |
| 10 | 67 | 67 | EPHS | 1465$^{abc}$ | 909$^{ba}$ | 1799$^{bcd}$ | 1676$^{ab}$ |
| 11 | 67 | 67 | FWF | 1555$^{ab}$ | 733$^{ba}$ | 1685$^{bcde}$ | 2057$^{a}$ |
| 12 | 67 | 67 | 30 DAFWF | 1252$^{be}$ | 880$^{ba}$ | 1753$^{bcd}$ | 1853$^{ab}$ |
| 13 | 101 | 33 | EPHS | 1495$^{abc}$ | 779$^{ba}$ | 1717$^{bcde}$ | 1665$^{ab}$ |
| 14 | 101 | 33 | FWF | 1523$^{ab}$ | 863$^{ba}$ | 1630$^{cdef}$ | 1735$^{ab}$ |
| 15 | 101 | 33 | 30 DAFWF | 1364$^{bcd}$ | 937$^{a}$ | 1793$^{abc}$ | 1300$^{b}$ |
| Mean | | | | 1365 | 818 | 1641 | 1631 |
| SED | | | | 98 | 129 | 177 | 279 |

$^{z}$ Treatment

$^{y}$ Lake Carl Blackwell

$^{x}$ Means in the same column followed by the same letter are not significantly different from each other at $P < 0.05$.

$^{w}$ Early pinhead square

$^{v}$ First white flower

$^{u}$ 30 d after first white flower

**Table 10. Analysis of variance for lint yield as affected by sidedress N applied at early pin head square, first white flower, and 30 d after first white flower cotton growth stages, in 2009 and 2010, Altus and Lake Carl Blackwell (LCB), OK.**

| Source of Variation | df | Mean squares | | | |
|---|---|---|---|---|---|
| | | 2009 | | 2010 | |
| | | Altus | LCB | Altus | LCB |
| Replication | 2 | 67715 | 64223 | 51237 | 35738 |
| Sidedress N rate | 3 | 52791* | 13092 | 112020 | 181924 |
| Growth stage | 2 | 564777*** | 19736 | 248595* | 263584 |
| Sidedress N x Growth stage | 6 | 55827** | 10355 | 162113* | 67783 |
| Residual error | 22 | 14619 | 29226 | 54959 | 116044 |

*, **, *** significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

At the same site in 2010, lint yield increased with preplant N rate (Table 9). Generally there was a significant ($P < 0.0001$) effect of treatments on lint yield that ranged from 829 to 2198 kg ha$^{-1}$. Growth stage and interaction between sidedress N and the time of application (growth stage) significantly ($P < 0.05$) led to lint yield increase (Table 10). Treatments with 0 or 33 kg N ha$^{-1}$ preplant had significantly ($P < 0.05$) higher lint yield than when sidedress N was applied at EPHS stage. When preplant N rate was increased to 67 kg N ha$^{-1}$, lint yields were still high when sidedress N was applied at EPHS but not significantly different from lint yields obtained from treatments that received sidedress N at FWF or 30 DAFWF. Application of high preplant N rate (101 kg N ha$^{-1}$) followed by 33 kg N ha$^{-1}$ sidedress N gave inconsistent results.

At LCB in 2009, there was no significant ($P <$ 0.05) effect of treatments on lint yield (Table 9 and 10). However, the lint yields were actually the lowest in the 134 kg N ha$^{-1}$ plots at 657 kg ha$^{-1}$, whereas the 0 N plot reached 841 kg ha$^{-1}$, suggesting not only no response to N but an inverse relationship of lint yield with high N application rates. Generally lint yields were the lowest compared to Altus and LCB 2010, mainly due excessive vegetative growth.

In 2010 at LCB, there was no significant ($P >$ 0.05) effect of treatments on lint yield (Table 9 and 10). However, lint yields slightly increased with preplant N rate. With exception of treatments that received 67 kg N ha$^{-1}$ preplant and sidedress N, high lint yields were recorded when sidedress N was applied at EPHS or FWF stage. Delaying sidedress N to 30 DAFWF, cotton lint yield declined.

## DISCUSSION

Nitrogen response in terms of NDVI and lint yield varied with site and cropping season. This finding further emphasizes the variability in optimum N rate and importance of accurate in-season N recommendation for increased lint yield and N-use efficiency. Positive increase in NDVI with preplant N application indicated that cotton could benefit from additional N. Therefore, SBNRC can be used to make precise in-season N recommendations for cotton using NDVI values from farmer's practice and N-rich strips. Application of low preplant N rates (0 or 33 kg N ha$^{-1}$) lead to N deficiency in cotton. However, at Altus in 2009, cotton catches up in lint yield when sidedress was applied by FWF. In the same site in 2010, cotton recovered from an early N deficiency when sidedress N was applied at EPHS. At LCB no response was recorded in 2009, and cotton recovered when sidedress N was applied at EPHS and FWF in 2010. The low lint yields at Altus in 2010 for treatments that received sidedress N at FWF could have been due to the influence of climatic conditions at the time of sidedress N application. The inadequacy of N required for boll and seed production at the time the crop needed N the most explains the decline in lint yields when sidedress N was applied at 30 DAFWF especially in 2009 (Altus) and 2010 (LCB).

Late sidedress N application instead encouraged "rank" growth, which was observed in plots where sidedress N application was delayed. Similar results were established by Stewart (1986) that at vegetative growth stage and 3 wk after flower appearance, cotton required adequate N for maximum boll and seed production, due to cotton's high demand for carbohydrates at this stages. These findings demonstrated that with correct timing of sidedress N, cotton can still recover for early N deficiency and attain near maximum lint yields. The correct growth stage when to sense the crop and apply sidedress, would still vary from site to site, and season to season.

Lack of significant differences in lint yield at LCB in 2009 was attributed to mineralization of organic N and a subsequent increase in the available N in the soil profile as the season progressed. As a result, high supply of N in the soil favored lush vegetative growth at the expense of lint yield production. Past findings have established that cotton has an indeterminate growth habit and if excess N is applied, its maturity will be delayed and lower lint yields obtained (McConnell et al., 1996).

## CONCLUSION

NDVI and lint yield increased with preplant N rate. Application of 0 or 33 kg N ha$^{-1}$ preplant contributed inadequate N to achieve maximum yield, especially at Altus. At high preplant N rates, cotton did not show any signs of N deficiency in both seasons and sites. With low preplant N rate application, cotton recovered from an early N deficiency and attained near maximum lint yields, as long as sidedress N fertilizer application was not delayed beyond FWF growth stage at Altus (2009) and LCB (2010). Delaying sidedress N application up to 30 DAFWF, lint yields were depressed. Cotton was able to catch up in lint yields at Altus (2010) when sidedress N was applied at EPHS. Delaying sidedress N application to FWF and 30 DAFWF resulted in decreased lint yields. The increase in NDVI with preplant N application indicated that additional N could benefit cotton growth and development. Based on this finding, SBNRC could be used to make mid-season N recommendations in cotton. This could eventually improve lint yield production and the efficiency of nitrogen fertilization in cotton.

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## REFERENCES

Arnall, D.B. 2008. Analysis of the coefficient of variation of remote sensor readings in winter wheat, and development of a sensor based mid-season N recommendation for cotton. Ph.D. diss. Oklahoma State Univ., Stillwater..

Guo, W. 2005. Spatial and temporal variability in cotton yield in relation to soil apparent electrical conductivity, topography, and remote sensing imagery. Ph.D. Diss. Texas Tech Univ., Lubbock..

Lege, K.E., J.T. Cothren, and P.W. Morgan, 1997. Nitrogen fertility and leaf age effect on ethylene production of cotton in a controlled environment. J. Plant Growth 22:23–28.

McConnell, J.S., W. H. Baker, and B.S. Frizzell. 1996. Distribution of residual nitrate-N in long term fertilization studies of an alfisol cropped for cotton. J. Environ. Qual. 25:1389–1394.

Raun, W.R., J.B. Solie, K.L. Stone, K.L. Martin, K.W. Freeman, R.W. Mullen, H. Zhang, J.S. Schepers, and G.V. Johnson. 2005. Optical Sensor Based Algorithm for Crop Nitrogen Fertilization. Commun. Soil Sci. Plant Anal. J. 36:2759–2781.

Raun, W.R., J.B. Solie, R.K. Taylor, D.B. Arnall, C.J. Mack, and D.E. Edmonds. 2008. Ramp calibration strip technology for determining midseason nitrogen rates in corn and wheat. Agron. J. 100:1088–1093.

SAS Institute. 2003. SAS/STAT Users Guide: Release 9.1. SAS Inst. Cary, NC.

Schepers, J.S., T.M. Blackmer, and D.D. Francis. 1992a. Predicting N fertilizer needs for corn in humid regions: using chlorophyll meters. p. 105–114 *In* B.R. Bock and K.R. Kelley (eds.). Predicting N Fertilizer Needs for Corn in Humid Regions. Bull. Y-226. National Fertilizer and Environmental Research Centre, Muscle Shoals, AL.

Schepers, J.S., D.D. Francis, M. Vigil, and F.E. Below. 1992b. Comparison of corn leaf nitrogen and chlorophyll meter reading. Commun. Soil Sci. Plant Anal. 23:2173–2187.

Stewart, J.M. 1986. Integrated events in the flower and fruit. p. 261–300 *In* J.R. Mauney and J.M. Stewart (eds.). Cotton Physiology, Vol. 1. The Cotton Foundation, Memphis, TN.

Texier, P.H. 1993. Le-cotton, cinquieme producteur mondial d'huile alimentaire. Cotton Develop. 8:2–3.

Tucker, C.J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. 8:127–150.

Wright, D., M.J. Marois, and J. Rich. 2003. Cotton Cultural Practices and Fertility Management. S-AGR-194. Agronomy Dept., Univ. Florida Ext., Gainesville, FL.

Zhao D. and D.M. Oosterhuis 2000. Nitrogen application effect on leaf photosynthesis, nonstructural carbohydrate concentrations and yield of field-grown cotton. Special Report, Arkansas Agric. Exp. Sta. No. 198: 69–71.