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In-Season Side-Dressing of Urea and Ammonium Nitrate to Cotton on No-Till Soils with High Residual Nitrogen and Pre-Plant Nitrogen Application

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Abstract

It is essential to develop innovative approaches that can apply N more efficiently. The objective of this study was to examine in-season side-dress urea and ammonium nitrate (UAN) applications to cotton on no-till soils with high residual N fertility. A field trial was conducted near Milan, TN in 2011 and 2012 with strip plots in a RCB design with three replicates. The following six in-season side-dress fluid UAN treatments were compared: 1) zero N; 2) low uniform-rate N application of 56 kg·N·ha^{-1}; 3) high uniform-rate N application of 78.4 kg·N·ha^{-1}; 4) ordinary variable-rate N application algorithm for each sub plot based on the average Normalized Difference Vegetation Index (NDVI) value in that sub plot; 5) reversed variable-rate N application algorithm for each sub plot based on average NDVI of that sub plot; and 6) N application rate based on the average NDVI value in each strip plot. All plots received 26 kg·N·ha^{-1} as diammonium phosphate before cotton planting each year. Leaf N concentrations were mostly enhanced with all side-dress N applications ranging from 56 to 78 kg·N·ha^{-1} relative to zero N during early to late bloom although this upland field had high initial soil N fertility and received pre-plant application of 26 kg·N·ha^{-1} across the treatments each year. However, NDVI, plant height, and lint yield were rarely improved with side-dress N application. The three variable-rate N application algorithms consumed 7.8 to 12.3 kg·ha^{-1} more N than the low uniform-rate application of 56 kg·N·ha^{-1}, but 10.1 to 14.6 kg·ha^{-1} less N than the high uniform rate of 78.4 kg·N·ha^{-1}. Our results indicate that the current N recommendations for cotton in Tennessee may be too high on upland soils with high initial N fertility.

Keywords

UAN, Side-Dress, Cotton, Yield, N Consumption

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1. Introduction

During the past several decades, the largest increase in the use of agricultural inputs has been fertilizer nitrogen (N) [1]. Nitrogen fertilization is a key production practice in most crops including cotton. Fertilizer N is one of the greatest cost inputs in cotton production. It is also the most difficult nutrient to manage, and has large potential adverse impacts on the environment. Under-application of N on cotton results in poor vegetative and reproductive growth, premature senescence, and reduced yields; while over-application inhibits boll formation and retention, poses serious threats to the environment [2], and reduces grower profitability. Due to substantially increased environmental concern and rising N price during the last decade, there is an urgent need to develop innovative systems and technologies that can apply N more efficiently so as to reduce N losses, increase crop yields and profitability, and improve environmental quality.

Nitrogen fertilizers are recommended to be applied at 67 - 90 kg·N·ha^{-1} (60 - 80 lb N acre^{-1}) on upland soils and 34 - 67 kg·N·ha^{-1} (30 - 60 lb N acre^{-1}) on bottom soils in Tennessee [3]. These recommendations have been used for decades without modifications although cotton production systems have been changed dramatically. For example, new cotton cultivars with high yield potentials have been continuously introduced to the market over the past decades. Due to security concern, urea and ammonium nitrate (UAN) and urea have been increasingly used to replace ammonium nitrate as the N source for cotton production in Tennessee. Presently, UAN is usually injected into the soil, while ammonium nitrate is broadcast on the soil surface. Traditionally, N fertilizer is applied around cotton planting, but split applications (a small portion of N as pre-plant plus a large portion of N as side-dress) have recently gained grower's attention. No-tillage systems are being widely used by producers in cotton production in Tennessee and throughout the southeastern USA. Under no-tillage, N fertilizer is often broadcast on soil surface without incorporation into the soil, while it is generally incorporated after surface application under conventional tillage systems [4]. Overall, information on cotton responses to the application rate, timing, and method of alternate N sources such as UAN and urea is limited under no-till production systems.

Furthermore, current fertilizer N recommendations are developed by individual states on small fields where spatial variances are minimal. Although recommendations may account for soil variations, growers do not have the technology to manage spatial variability within individual fields. Under the current systems, producers use a uniform N fertilizer rate across entire fields, which often results in over- and under-applications of N because crop responses to N fertilization are often variable within individual fields [5], and on some parts of the field more N should be applied or much less to none on other parts of the field [6]. Therefore, the presence of spatial variability within individual fields is a critical issue demanding careful management. In order to solve this problem, it is essential to develop and adopt innovative technologies and management systems that can generate and implement variable-rate fertilizer N recommendations based on spatial variances within individual fields.

Measuring crop N nutrition status during the growing season by optically sensing crop canopy has been developed into a viable precision N management tool during the last several years [7] [8]. Researchers utilize on-vehicle, real-time optical sensing of crop canopy reflectance which can be used to develop indices such as the Normalized Difference Vegetation Index (NDVI) to assess crop growth, health, or N nutritional status and use these indices to adjust the fertilizer N rate accordingly. Integration of optical sensing and variable-rate application technologies enables on-the-go non-destructive diagnoses of crop N deficiency, sufficiency, or excesses without soil or plant tissue diagnostic testing, real-time application of N fertilizer at variable rates to correct those deficiencies or excesses, and precisely treating each part of the field sensed. Since this is real-time sensing, it is done without pre-processing of data or determining location within field beforehand. This innovative precision technology allows variable application of N fertilizers at very high resolutions. So far this system is the most efficient technology for precision N management as it can change uniform-rate N application to variable-rate N applications, minimizing time, labor, and cost of implementing variable-rate N applications [8] [9], which is vastly different from the traditional N management systems of uniform rate N applications across entire fields.

Investigations have shown significant economic and environmental benefits with optical sensor-based variable-rate precision N management technologies and systems. Research on corn and winter wheat have shown 10% - 15% increases in N use efficiency and some significant yield increases with these precision N management systems relative to the traditional uniform-rate N management systems [6] [8]. Biermacher *et al*. (2006) [10] in Oklahoma even reported as high as 59% - 82% reductions in N fertilizer use by winter wheat under the optical sensor-based variable-rate N management systems. Ortiz-Monasterio and Raun (2007) [11] showed that optical sensor-based precision N management systems can save 71 kg·N·ha^{-1} on spring wheat and increase grower profitability by \$148 ha^{-1}. However, investigations on cotton responses to variable-rate N applications based on canopy NDVI were limited.

The objective of this study was to examine in-season side-dress UAN application systems (both variable-rate and uniform rate) for cotton on no-till soils with high residual N fertility and pre-plant N application in terms of N fertilizer consumption, lint yield and quality, and residual N in the soil profile.

2. Materials and Methods

A field trial was conducted on the University of Tennessee Research and Education Center at Milan in 2011 and 2012 with the following six in-season side-dress UAN treatments evaluated in strip plots. Each strip plot was divided into 8 sub plots (7.5 m wide × 15 m long).

1) Zero N;

2) Low uniform-rate N application of 56 kg·N·ha^{-1} (50 lb N a^{-1}) over each strip plot;

3) High uniform-rate N application rate of 78.4 kg·N·ha^{-1} (70 lb N a^{-1}) over each strip plot;

4) Ordinary variable-rate N application algorithm in the range of 33.6 to 100.8 kg·ha^{-1} (30 to 90 lb a^{-1}) of N for each sub plot based on the average NDVI value in that sub plot;

5) Reversed variable-rate N application algorithm in the range of 33.6 to 100.8 kg·ha^{-1} (30 to 90 lb a^{-1}) of N for each sub plot based on the average NDVI value in that sub plot;

6) Nitrogen application rate based on the average NDVI value in each strip plot.

No side-dress UAN fertilizer was applied in any strip or sub plot in Treatment 1. Nitrogen fertilizer of 56 kg·N·ha^{-1} was applied to all sub plots in each strip plot in Treatment 2. Nitrogen fertilizer at 78.4 kg·N·ha^{-1} was applied to all sub plots in each strip plot in Treatment 3. The N application rates in Treatments 2 & 3 roughly represented the lower and higher limits of side-dress N applications used by cotton producers after approximately 22 to 34 kg·N·ha^{-1} (20 to 30 lb N a^{-1}) was pre-plant applied as monoammonium phosphate or diammonium phosphate. Nitrogen applications in Treatments 4 to 6 were based on NDVI readings. In Treatment 4, when the NDVI reading was lower, more N fertilizer was applied. However, in Treatment 5, when the NDVI reading was lower, less N fertilizer was applied. In-season fluid N application rate ranged from 33.6 to 100.8 kg·ha^{-1} for both Treatments 4 and 5. In Treatment 6, the N application rate was identical for all sub plots within a strip plot, but it might be different among the three strip plots of the three replicates since it was based on the average NDVI value in each strip plot. Fluid N fertilizer UAN (32-0-0) was injected 3.8 cm deep into the soil and 25.4 cm to one side of the row with a KBH 8-row pull-type coulter injector for all the in-season applied N treatments (Treatments 2 to 6). In addition to the above in-season N treatments, all the plots received 26 kg·N·ha^{-1} and 67 kg P_2O_5 ha^{-1} as diammonium phosphate and 67 kg K_2O ha^{-1} as muriate of potash regardless of treatment in fall 2010. In March 2012, 26 kg·N·ha^{-1}, 67 kg P_2O_5 ha^{-1}, and 101 kg K_2O ha^{-1} were applied to all the plots irrespective of the treatment. The P and K fertilizers were broadcast applied based on the soil testing results each year.

The test field had four different soil types: Calloway, Falaya, Grenada, and Lexington. The initial soil nitrate- and ammonium-N content within the top 60 cm of soil varied substantially ranging from 3 to 57 mg·kg^{-1}. All these suggest that the test field is spatially variable.

The dates of cotton planting, N treatment implementation, and other major field operations for this test are presented in **Table 1**. A composite soil sample was collected at a depth of 60-cm for nitrate and ammonium in the soil profile on a sub plot basis prior to treatment initiation. The following sampling and measurements were taken from each sub plot each year: Canopy NDVI data were recorded at the early square and early, mid, and late bloom growth stages using the GreenSeeker® RT 200 Data Collection and Mapping System (NTech Industries, Inc., CA). A composite leaf sample (10 blades + 10 petioles) was collected four times at about the same dates when NDVI data were taken. All leaf samples were analyzed for N concentrations using a LECO Tru-Spec Analyzer. Cotton harvest was completed timely for lint yield and gin turnout by harvesting the center 4 rows. In addition, fiber quality attributes were determined on a strip plot basis each year. A post-harvest soil sample was taken for soil nitrate and ammonium at a 60-cm depth.

Analysis of variance was conducted for each measurement with a randomized complete block model using SAS statistical software (SAS Institute, Cary, NC). Treatment means were separated with the Fisher's protected

Table 1. Major field operations performed on this trial in 2011 and 2012.

Year	List of Operations Performed	Date Performed
2011	Planted DPL 0912 with a 8-row planter	05/11/11
	Collected pre-treatment soil samples to 60 cm deep (2 cores $plot^{-1}$)	05/26/11
	Recorded canopy NDVI prior to N treatment	06/24/11
	Side-dressed fluid N treatments by plot	07/12/11
	Collected early square leaf samples (10 leaves $plot^{-1}$)	07/12/11
	Recorded early square plant height (10 plants $plot^{-1}$)	07/12/11
	Recorded canopy NDVI at early bloom	07/21/11
	Collected early bloom leaf samples (10 leaves $plot^{-1}$)	07/22/11
	Recorded early bloom plant height (10 plants $plot^{-1}$)	07/22/11
	Recorded canopy NDVI at mid bloom	08/01/11
	Collected mid bloom leaf samples (10 leaves $plot^{-1}$)	08/02/11
	Recorded mid bloom plant height (10 plants $plot^{-1}$)	08/02/11
	Recorded canopy NDVI at late bloom	08/15/11
	Collected late bloom leaf samples (10 leaves $plot^{-1}$)	08/12/11
	Recorded late bloom plant height (10 plants $plot^{-1}$)	08/12/11
	Harvested center 4 rows of each 8 row plot & collected seed cotton samples by strip plot	10/11/11
	Collected post-harvest soil samples to 60 cm deep (2 cores $plot^{-1}$)	11/07/11
2012	Planted DPL 0912 with a 8-row planter	05/10/12
	Recorded canopy NDVI prior to N treatment	07/11/12
	Collected early square leaf samples (10 leaves $plot^{-1}$)	07/11/12
	Recorded early square plant height (10 plants $plot^{-1}$)	07/11/12
	Side-dressed fluid N treatments by plot	07/18/12
	Recorded canopy NDVI at early bloom	07/19/12
	Collected early bloom leaf samples (10 leaves $plot^{-1}$)	07/19/12
	Recorded early bloom plant height (10 plants $plot^{-1}$)	07/19/12
	Recorded canopy NDVI at mid bloom	07/26/12
	Collected mid bloom leaf samples (10 leaves $plot^{-1}$)	07/26/12
	Recorded mid bloom plant height (10 plants $plot^{-1}$)	07/26/12
	Recorded canopy NDVI at late bloom	08/08/12
	Collected late bloom leaf samples (10 leaves $plot^{-1}$)	08/08/12
	Recorded late bloom plant height (10 plants $plot^{-1}$)	08/08/12
	Harvested center 4 rows of each 8 row plot & collected seed cotton samples by strip plot	10/25/12
	Collected post-harvest soil samples to 60 cm deep (2 cores $plot^{-1}$)	11/09/12

LSD method. In addition, nonorthogonal contrasts were conducted in order to compare means of treatment combinations. Probability levels lower than 0.05 were designated as significant.

3. Results and Discussion

3.1. Initial Soil N Fertility

Initial inorganic N (NO_3^--N + NH_4^+-N) content in the top 60 cm of soil varied substantially among the 144 sub plots with a range of the minimum 3 mg·kg^{-1} to the maximum 57 mg·kg^{-1} after this field had received 26 kg·N ha^{-1} as diammonium phosphate in fall 2010 but before the in-season side-dress N treatments were applied in spring 2011 in this study (data not presented). These variations might relate to the soil types in this field. The average initial inorganic N level in the top 60 cm of soil was 6.8, 7.4, 9.8, 8.0, 10.4, and 8.8 mg·kg^{-1}, equivalent to 60.8, 66.4, 88.0, 71.6, 93.2 and 78.8 kg·ha^{-1}, for the plots allocated to Treatments 1, 2, 3, 4, 5, and 6, respectively, before treatment application in spring 2011. Obviously this field had pretty high residual inorganic N level in the soil profile from the previous crop production. High residual inorganic N level in soil profile has been increasingly observed in cotton and corn production in Tennessee and other states.

3.2. Effects of In-Season Side-Dress N Applications on Leaf N Concentrations

Leaf N concentrations were similar among the plots allocated to Treatments 1, 2, 3, 4, 5, and 6, respectively at early square before the in-season side-dress N treatments were applied when the results of 2011 and 2012 were combined (**Table 2**). However, significant differences in leaf N were observed among the six treatments at the early, mid, and late bloom stages (**Table 2**). Leaf N concentrations were mostly significantly higher under the five N applied treatments than those with the zero N treatment (Treatment 1) during early bloom to late bloom. Treatments 3, 4, and 5 had significantly higher leaf N concentrations than Treatment 1, and significantly or numerically higher leaf N levels than Treatments 2 and 6 at the early, mid, and late bloom stages.

Under nonorthogonal contrasts, Applied N, Uniform N, and Variable N all resulted in significantly higher leaf N concentrations than Zero N at the early, mid, and late bloom stages (**Table 2**). However, Variable N had similar leaf N level as Uniform N regardless of growth stage.

Both ANOVA and nonorthogonal contrast analyses of this study indicate that in-season side-dress N application improves cotton N nutrition irrespective of the application method (uniform-rate or variable-rate); but variable-rate N applications do not improve cotton N nutrition compared with uniform-rate N applications on this upland field with high initial soil N fertility.

It was expected that leaf N concentration was pretty high under the zero N treatment regardless of growth stage, which might relate to the fact that the initial inorganic N level was high in the top 60 cm of soil profile

Table 2. Effects of in-season side-dress N applications on leaf N concentrations at different growth stages averaged over 2011 and 2012.

Treatment	Early Square	Early Bloom	Mid Bloom	Late Bloom
	g·kg^{-1}	g·kg^{-1}	g·kg^{-1}	g·kg^{-1}
1	40.5a†	38.3c	35.8c	34.4b
2	40.4a	40.8ab	36.8bc	36.9ab
3	40.7a	41.7ab	38.4a	38.8a
4	41.3a	41.4ab	37.6ab	37.3a
5	41.8a	42.3a	37.7ab	38.4a
6	39.6a	40.2bc	37.0bc	36.5ab
Significance	ns‡	**	**	*
Contrast				
Applied N vs. Zero N§	ns	***	**	**
Uniform N vs. Zero N	ns	**	**	**
Variable N vs. Zero N	ns	**	**	**
Variable N vs. Uniform N	ns	ns	ns	ns

†Values within a column followed by the same letter are not significantly different with Fisher's protected LSD at the 0.05 probability level. ‡*significant at $P < 0.05$; **significant at $P < 0.01$; ***significant at $P < 0.001$; ns, not significant at $P < 0.05$. §Applied N vs. Zero N refers to the comparison of average over the five N applied treatments (Treatments 2, 3, 4, 5, and 6) with the Zero N treatment (Treatment 1); Uniform N vs. Zero N refers to the comparison of average over the two uniform-rate N treatments (Treatments 2 and 3) with the Zero N treatment; Variable N vs. Zero N refers to the comparison of average over the three variable-rate N treatments (Treatments 4, 5, and 6) with the zero N treatment; Variable N vs. Uniform N refers to the comparison of average over the three variable-rate N treatments with the two uniform-rate N treatments.

and 26 kg·N·ha^{-1} was applied across the treatments as diammonium phosphate before cotton planting in both years.

The sensitivity of cotton leaf N to N application is greater at early bloom than at any other growth and developmental stages [12] [13]. This trend indicates monitoring of leaf N nutrition status at early bloom is especially helpful in deciding whether supplemental N application is required. Campbell and Plank (2011) [14] recommended that the range of adequate leaf N concentration be 30 to 45 g·kg^{-1} at early bloom for cotton grown in the southern United States. According to this criterion, leaf N concentration at early bloom was greater than the lower limit of the sufficiency range in the zero N treatment of this study. Similarly, the range of adequate leaf N concentration is recommended to be 30 to 45 g·kg^{-1} at late bloom for cotton [14]. According to this standard, leaf N at late bloom was also above the lower limit of the sufficiency range in zero N. Therefore, cotton yield responses to N applications might not be expected, based on the adequate leaf N nutrition under the zero N treatment, if the recommended sufficiency leaf N ranges during early to late bloom are indicative of final cotton yield, although the in-season N applied treatments mostly resulted in higher N concentrations than the zero N treatment in this study.

3.3. Effects of In-Season Side-Dress N Applications on Canopy NDVI Readings

Canopy NDVI is a good vegetation index that can be used to estimate plant N nutrition status and plant biomass. Canopy NDVI readings were statistically similar among the six treatments at early square before the N treatments were implemented averaged over 2011 and 2012 (**Table 3**). Unlike leaf N concentrations, no significant difference in NDVI was observed among the six treatments at early, mid, or late bloom stage (**Table 3**). Similarly, nonorthogonal contrasts did not show any beneficial effect of Applied N, Uniform N, or Variable N on NDVI over Zero N at any growth stage (**Table 3**).

3.4. Effects of In-Season Side-Dress N Applications on Plant Height

Similar to leaf N and canopy NDVI, plant height did not differ significantly among the six treatments at early square prior to N treatment implementation averaged 2011 and 2012 (**Table 4**). However, plant height was significantly different among the six treatments at the early bloom stage (**Table 4**). Plants at early bloom were

Table 3. Effects of in-season side-dress N applications on canopy NDVI at different growth stages averaged over 2011 and 2012.

Treatment	Early Square	Early Bloom	Mid Bloom	Late Bloom
1	0.55a†	0.69a	0.70a	0.73a
2	0.57a	0.70a	0.71a	0.73a
3	0.58a	0.70a	0.71a	0.73a
4	0.56a	0.69a	0.70a	0.73a
5	0.55a	0.70a	0.72a	0.75a
6	0.58a	0.68a	0.70a	0.72a
Significance	ns‡	ns	ns	ns
Contrast				
Applied N vs. Zero N§	ns	ns	ns	ns
Uniform N vs. Zero N	ns	ns	ns	ns
Variable N vs. Zero N	ns	ns	ns	ns
Variable N vs. Uniform N	ns	ns	ns	ns

†*Values within a column followed by the same letter are not significantly different with Fisher's protected LSD at the 0.05 probability level. ‡ns, not significant at $P < 0.05$. §Applied N vs. Zero N refers to the comparison of average over the five N applied treatments (Treatments 2, 3, 4, 5, and 6) with the zero N treatment (Treatment 1); Uniform N vs. Zero N refers to the comparison of average over the two uniform-rate N treatments (Treatments 2 and 3) with the zero N treatment; Variable N vs. Zero N refers to the comparison of average over the three variable-rate N treatments (Treatments 4, 5, and 6) with the zero N treatment; Variable N vs. Uniform N refers to the comparison of average over the three variable-rate N treatments with the two uniform-rate N treatments.

Table 4. Effects of in-season side-dress N applications on plant height at different growth stages averaged over 2011 and 2012.

Treatment	Early Square	Early Bloom	Mid Bloom	Late Bloom
	cm	cm	cm	cm
1	64.3a†	81.8b	93.0a	98.6a
2	66.5a	81.0b	93.5a	100.6a
3	67.3a	85.9a	97.3a	101.9a
4	66.0a	82.3b	93.7a	99.6a
5	65.5a	81.3b	93.7a	100.6a
6	66.5a	80.5b	92.7a	99.8a
Significance	ns‡	*	ns	ns
Contrast				
Applied N vs. Zero N§	ns	ns	ns	ns
Uniform N vs. Zero N	ns	ns	ns	ns
Variable N vs. Zero N	ns	ns	ns	ns
Variable N vs. Uniform N	ns	*	ns	ns

†*Values within a column followed by the same letter are not significantly different with Fisher's protected LSD at the 0.05 probability level. ‡*significant at $P < 0.05$; ns, not significant at $P < 0.05$. §Applied N vs. Zero N refers to the comparison of average over the five N applied treatments (Treatments 2, 3, 4, 5, and 6) with the zero N treatment (Treatment 1); Uniform N vs. Zero N refers to the comparison of average over the two uniform-rate N treatments (Treatments 2 and 3) with the zero N treatment; Variable N vs. Zero N refers to the comparison of average over the three variable-rate N treatments (Treatments 4, 5, and 6) with the zero N treatment; Variable N vs. Uniform N refers to the comparison of average over the three variable-rate N treatments with the two uniform-rate N treatments.

significantly taller under Treatment 3 which received the highest in-season side-dress N application rate than those with the other treatments.

3.5. Effects of In-Season Side-Dress N Applications on Lint Yield, Gin Turnout, and Fiber Quality

Lint yield responses to in-season side-dress N treatments were not significant on the averages of 2011 and 2012 (**Table 5**). Numerically, lint yields were higher under Treatments 2 and 5 than those with the other treatments. Gin turnout was not significantly affected by the N treatments (data not presented). None of the fiber quality attributes was influenced by the N treatments (**Table 5**).

Similarly, Main *et al.* (2013) [15] reported only 11 of 20 site-years across the Cotton Belt region in which there was a cotton lint yield response to applied N. They observed when 45 $kg \cdot N \cdot ha^{-1}$ was applied, yields were greater than when no N was applied, but were less than yields where 90 to 134 $kg \cdot N \cdot ha^{-1}$ was applied on the N responsive site-years; however, when all the site-years, both N responsive and non-responsive, were considered, 45 $kg \cdot N \cdot ha^{-1}$ increased yields above no applied N, but additional N above 45 $kg \cdot N \cdot ha^{-1}$ did not improve lint yield.

3.6. Effects of In-Season Side-Dress N Applications on In-Season N Fertilizer Consumption

The in-season side-dress N fertilizer consumption was 0, 56.0, 78.4, 68.7, 63.5, and 67.2 $kg \cdot N \cdot ha^{-1}$ for Treatments 1 to 6, respectively, averaged over 2011 and 2012 in this study (**Table 6**). The three variable-rate N application algorithms (Treatments 4, 5, and 6) consumed 7.8 to 12.3 $kg \cdot ha^{-1}$ more N than the low uniform-rate application of 56.0 $kg \cdot N \cdot ha^{-1}$, but used 10.1 to 14.6 $kg \cdot ha^{-1}$ less of N than the high uniform rate application of 78.4 $kg \cdot N \cdot ha^{-1}$. Under nonorthogonal contrasts, Applied N, Uniform N, and Variable N all consumed more in-season side-dress N fertilizer than the Zero N treatment, but Variable N used similar in-season side-dress N fertilizer as Uniform N (**Table 6**).

The total annual N application rate (pre-plant N + in-season side-dress N) was 26, 82, 104.4, 94.7, 89.5, and

Table 5. Effects of in-season side-dress N applications on lint yield, gin turnout, and fiber quality averaged over 2011 and 2012.

Treatment	Yield	Micronaire	Strength	Length	Uniformity
	kg·ha^{-1}		g tex^{-1}	cm	%
1	1037.0a†	4.95a	32.9a	2.84a	83.2a
2	1127.7a	4.90a	33.3a	2.82a	83.3a
3	1076.4a	4.95a	32.2a	2.77a	82.3a
4	1089.2a	4.95a	33.0a	2.82a	82.9a
5	1155.5a	4.85a	33.1a	2.82a	83.7a
6	1075.5a	5.00a	32.2a	2.77a	82.7a
Significance	ns‡	ns	ns	ns	ns
Contrast					
Applied N vs. Zero N§	ns	ns	ns	ns	ns
Uniform N vs. Zero N	ns	ns	ns	ns	ns
Variable N vs. Zero N	ns	ns	ns	ns	ns
Variable N vs. Uniform N	ns	ns	ns	ns	ns

†*Values within a column followed by the same letter are not significantly different with Fisher's protected LSD at the 0.05 probability level. ‡ns, not significant at $P < 0.05$. §Applied N vs. Zero N refers to the comparison of average over the five N applied treatments (Treatments 2, 3, 4, 5, and 6) with the zero N treatment (Treatment 1); Uniform N vs. Zero N refers to the comparison of average over the two uniform-rate N treatments (Treatments 2 and 3) with the zero N treatment; Variable N vs. Zero N refers to the comparison of average over the three variable-rate N treatments (Treatments 4, 5, and 6) with the zero N treatment; Variable N vs. Uniform N refers to the comparison of average over the three variable-rate N treatments with the two uniform-rate N treatments.

Table 6. Effects of in-season side-dress N applications on in-season side-dress N consumption and post-harvest soil residual N (0 - 60 cm) averaged over 2011 and 2012.

Treatment	Side-Dress N Consumption	Soil Residual N
	kg·ha^{-1}	mg·kg^{-1}
1	0c†	7.65a
2	56.0b	7.28a
3	78.4a	8.58a
4	68.7ab	8.95a
5	63.5ab	9.36a
6	67.2ab	7.78a
Significance	***‡	ns
Contrast		
Applied N vs. Zero N§	***	ns
Uniform N vs. Zero N	***	ns
Variable N vs. Zero N	***	ns
Variable N vs. Uniform N	ns	ns

†*Values within a column followed by the same letter are not significantly different with Fisher's protected LSD at the 0.05 probability level. ‡***significant at $P < 0.001$; ns, not significant at $P < 0.05$. §Applied N vs. Zero N refers to the comparison of average over the five N applied treatments (Treatments 2, 3, 4, 5, and 6) with the zero N treatment (Treatment 1); Uniform N vs. Zero N refers to the comparison of average over the two uniform-rate N treatments (Treatments 2 and 3) with the zero N treatment; Variable N vs. Zero N refers to the comparison of average over the three variable-rate N treatments (Treatments 4, 5, and 6) with the Zero N treatment; Variable N vs. Uniform N refers to the comparison of average over the three variable-rate N treatments with the two uniform-rate N treatments.

93.2 kg·N·ha^{-1} for Treatments 1, 2, 3, 4, 5, and 6, respectively, averaged over 2011 and 2012. Since this study was conducted on an upland soil, the results of this study indicate that the current N fertilizer recommendations (67 to 90 kg·N·ha^{-1} for upland soils, and 34 to 67 kg·N·ha^{-1} for bottom soils) made by University of Tennessee [3] may be too high for cotton production on those upland fields with high residual soil inorganic N fertility in Tennessee. Since high residual inorganic N in soil profile has been increasingly observed on corn and cotton fields, it may be beneficial to take the results of pre-plant soil inorganic N test into consideration when the N fertilizer recommendations are made.

3.7. Effects of In-Season Side-Dress N Applications on Post-Harvest Soil Residual N Contents

An important aspect of N management strategies should be the reduction of soil residual N. Reducing N application rates for cotton, when appropriate, will reduce post-harvest residual N levels in the soil profile, and thus decrease the loss of N from soil to ground and surface waters.

No significant differences were observed in post-harvest soil residual N (NO_3^--N + NH_4^+-N) level in the top 60 cm soil profile among the six treatments on the averages of 2011 and 2012 (**Table 6**). Numerically, soil residual N level was higher under Treatments 3, 4, and 5 than those with the other treatments after cotton harvest. Overall, our results suggest that the application of in-season side-dress N ranging from 0 to 78.4 kg·N·ha^{-1} do not significantly affect the post-harvest residual N levels in the soil profile, which may relate to the possibility that applied N was either taken up by cotton plants or lost out of the soil via nitrate leaching to deeper layers or ammonium volatilization to the atmosphere during the growing season.

Boquet and Breitenbeck (2000) [16] reported that N fertilization on cotton for optimal yield was exceptionally efficient and probably did not result in N losses to nearby surface and ground waters. In contrast, soil samples collected after 3 years of continuous N fertilization resulted in a significant increase in NO_3^--N concentration at the 15 - 45 cm depth only in the plots treated with the highest N rate of 224 kg·N·ha^{-1} annually [17]. Results of a 5-yr study showed excessive N buildup in many California cotton soils due to the high N application rates for previous cotton or other rotational crops [18]. Bronson *et al*. (2001) [19] found that residual soil NO_3^--N accumulated to high levels in the low irrigation, high N fertilizer treatments, but remained stable in the high irrigation, low N treatments.

4. Conclusions

Leaf N concentrations were generally improved by in-season side-dress N applications of 56 to 78 kg·N·ha^{-1} compared with those under the zero side-dress N control during early to late bloom even though this upland field held high initial soil inorganic N fertility and 26 kg·N·ha^{-1} was applied across the treatments before cotton planting each year. However, rare significant differences in cotton growth (canopy NDVI and plant height) were observed because of in-season N applications during early or late bloom stages. Lint yield was not significantly improved by either variable-rate or uniform-rate N applications via side-dress during the growing season. The three variable-rate N application algorithms consumed 7.8 to 12.3 kg·ha^{-1} more N than the low uniform-rate application of 56 kg·N·ha^{-1}, but used 10.1 to 14.6 kg·ha^{-1} less of N than the high uniform-rate application of 78.4 kg·N·ha^{-1}. No significant positive effect of in-season side-dress N applications was observed on post-harvest soil residual N levels. Our results suggested that it might be difficult to obtain cotton yield responses to in-season side-dress N applications or compare in-season variable-rate N applications with the traditional uniform-rate N applications in terms of cotton yields on those upland fields that held high initial soil N fertility and had received pre-plant N application.

Since this study was conducted on an upland soil, the results of this study indicated that the current N fertilizer recommendations of 67 to 90 kg·N·ha^{-1} for cotton on upland soils made by University of Tennessee [3] might be too high for cotton production on those upland fields with high initial soil inorganic N fertility in Tennessee. Since high residual inorganic N in soil profile had been increasingly observed on corn and cotton fields, it might be beneficial to take the results of pre-plant soil inorganic N test into consideration when the N fertilizer recommendations were made.

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