INFLUENCE OF NITROGEN APPLICATION RATE ON THE YIELD, QUALITY, AND CHEMICAL COMPONENTS OF FLUE-CURED TOBACCO, PART II: APPLICATION METHOD

M.P. Drake[1], M.C. Vann[2]*, and L.R. Fisher[2]

Research was conducted in 2012 and 2013 to determine the effect of nitrogen application timing and method on the yield, quality, and leaf chemistry of flue-cured tobacco. Liquid urea–ammonium–nitrate supplied 100% of the total nitrogen and was applied in differing combinations of rates, timings, and methods. Nitrogen rates above, at, and below recommendation for specific locations were split into two, three, or four application timings depending on treatment. Nitrogen application was initiated at transplanting and concluded before or at topping. Applications of nitrogen were either soil applied at each interval or were soil applied until topping where application occurred over top to promote stalk rundown. Leaf tissue samples were collected at layby and topping to evaluate total nitrogen content throughout the growing season. Composite cured leaf tissue samples from all four stalk positions were analyzed for total alkaloid and reducing-sugar content. Yield data were collected and leaf quality was determined according to U.S. Department of Agriculture grade. Crop value per hectare was determined using a combination of yield and quality. Data were subjected to analysis of variance using the PROC GLM procedure in SAS ver. 9.4. Treatment means were separated using Fisher's Protected LSD at $P \leq 0.05$. Soil-applied treatments yielded higher than stalk rundown treatments but contained lower nitrogen content at topping and chlorophyll level (SPAD) measurements. Leaf quality was similar when nitrogen was applied as a stalk rundown at above recommended rates and when soil applied at recommended rates. Leaf value and total alkaloid content were not affected by treatments; however, sugar content was highest when less nitrogen was applied early in the season. Leaf nitrogen was higher at layby when a larger percentage of nitrogen was applied earlier in the season. Rainfall played a significant role in observed results and producers should exercise similar treatments with caution.

Additional key words: nitrogen, nitrogen application method, nitrogen application timing

INTRODUCTION

Nitrogen is considered to be the most important nutrient in the production of flue-cured tobacco (*Nicotiana tabacum* L.). Appropriate uptake of the nutrient is required to produce high-yielding, quality leaf with suitable aroma and smoke flavor (10). Flue-cured tobacco will accumulate approximately 50% of the total nitrogen applied in a season within 5 weeks after transplanting (14). Remaining nitrogen demand will be satisfied within an additional 4 to 5 weeks (8 to 9 weeks posttransplanting) (14). Nitrogen must be applied in adequate amounts to ensure availability to the plant during the essential stages of growth to have the greatest influence on chemical properties of the leaf (2). Too little nitrogen reduces yield and produces immature leaves that are pale and slick once cured (16). Smoke flavor and aroma from cured leaves deficient in nitrogen are noted as being flat and insipid (8). Overfertilization of nitrogen has potential to increase yield slightly but may also result in increased sucker pressure, delayed maturity, delayed ripeness, increased difficulty of mechanical harvest, and extended curing time (16). Excess nitrogen can result in leaves that are dark brown to black in color with dry, chaffy texture and a strong, pungent flavor (8,10).

*Corresponding author: M.C. Vann; email: matthew_vann@ncsu.edu
[1]Universal Leaf North America, 3174 Boddie Mill Pond Road, Nashville, NC 27856.
[2]Crop Science Department, North Carolina State University, Raleigh, NC 27695-7620.

Leaf maturity and ripeness have a profound effect on leaf quality; however, these two characteristics are not the same (17). Leaf maturity is correlated with age of the tobacco plant, whereas ripeness is a factor of nitrogen attenuation as the growing season progresses (16). Because of the unique harvesting of the vegetative portion of the tobacco plant, leaves at different stalk positions will be at different physiological growth stages at any specific point in time (10). To ensure proper leaf quality it is important that a decline in nitrogen metabolism occurs as the plant reaches maximum leaf area (10). This decline in nitrogen after maximum leaf area is reached allows for the harvest of properly ripened leaves without losing yield potential.

Flue-cured tobacco is generally produced on sandy and sandy loam soils (8). With variation in soil type, nitrogen recommendations vary as well. Coarse soil types with deep Ap horizons may require a base nitrogen application rate of 89 kg/ha, whereas soils with a larger percentage of clay may only require 56 kg/ha (3). Current recommendations for producers in the United States reflect these principles (16). Being the most important nutritional component of a fertility program, nitrogen is relatively abundant in the flue-cured tobacco plant, second only to potassium (14). Traditional flue-cured tobacco-producing soils are typically comprised of a coarse soil texture, are very well drained, and contain less than 1% organic matter (13). In these systems soil nitrogen reserves are often very low, which adds to the importance of proper nitrogen fertilizer application rates (13). It is not uncommon for tobacco produced on these specific soil types to experience significant nitrogen leaching due to excessive precipitation. Nitrogen lost from the rooting zone can result in high-sugar, low-nicotine leaf chemistry (13). Overfertilized or drought-stressed tobacco will result in low sugar and high nicotine content due to excessive nitrogen absorption or moisture stress, which reduces vegetative growth (13). Neither production scenario is desirable for the production of quality leaf.

Because of the leaching potential of nitrate nitrogen, many growers have altered their approach to fertility programs. According to McCants and Woltz (10), when nitrate nitrogen is less than 30% of the total nitrogen source applied, reduced growth can occur as a result of ammonium toxicity. However, under present soil and climatic conditions as well as production standards, this has not been observed. Parker (12) verified that nitrogen source did not affect flue-cured tobacco yield, leaf quality, value, total alkaloid content, reducing-sugar content, or leaf color. A transition in management to a fertility program where all, or at least a percentage, of the total nitrogen is applied from liquid nitrogen can reduce nitrogen loss in a cropping system and decrease input cost without compromising yield or quality. The use of liquid material as a source of nitrogen has become a popular practice, with approximately 50% of the North Carolina flue-cured tobacco crop (>35,000 ha) receiving at least a portion of total nitrogen from this source (16).

Current nitrogen rates applied to a tobacco crop are based on soil type, cultural practices, and field history (16). With past research efforts focusing on nitrogen source and application rate, additional information is needed to determine the feasibility of splitting nitrogen applications into multiple applications without loss of yield or quality and without detrimental effects on leaf chemistry. Applying nitrogen in more than 2 applications would allow producers to base nitrogen rates on current growing conditions in conjunction with field history. With nitrogen availability being so closely correlated to weather conditions, and leaf quality being directly related to nitrogen availability, a new nitrogen regimen of more than 2 applications in a given season could assist growers in producing quality tobacco without reducing yield.

Application timing of nitrogen is critical to leaf maturity, ripening, and curability and was evaluated in a separate study (4). An additional aspect of late-season nitrogen application is the method in which nitrogen is applied. Late-season nitrogen application is feasible when using a high-clearance sprayer in conjunction with liquid materials. The adaptation of a high-clearance sprayer allows for nitrogen application directly to the soil surface or through a stalk rundown application similar to what is utilized for suckercide application. Current information for these late-season application methods does not exist; therefore, research was conducted to quantify differences between application methods. Research was initiated in 2012 and continued in 2013 to evaluate the response of flue-cured tobacco to differing late-season nitrogen application methods.

METHODS AND MATERIALS

Field Procedures. Research was conducted at the Border Belt Tobacco Research Station (BBTRS) near Whiteville, NC and the Oxford Tobacco Research Station (OTRS) in Oxford, NC in 2012. In 2013, research was continued at OTRS and the Upper Coastal Plains Research Station (UCPRS) near Rocky Mount, NC. Field conditions and monthly rainfall varied by growing location and are listed in Tables 1 and 2, respectively. Tobacco was produced using recommendations from the North Carolina Cooperative Extension Service (7), with the exception of treatments imposed. After curing, leaves were weighed to quantify yield and assigned a U.S. Department of Agriculture grade, which is based on leaf maturity and ripeness. Grades are assigned a monetary value and have an associated index value that quantifies leaf quality (1).

Treatments consisted of nitrogen applications made in differing combinations of rate, timing, and method. Six treatments were evaluated utilizing all possible combinations of 3 nitrogen application timings (50% of total recommended nitrogen split applied after layby, 50% of total recommended nitrogen applied at topping, and 25% above total recommended nitrogen applied at topping) and 2 application methods (direct soil application and stalk rundown). Two additional treatments were also evaluated for comparison between standard nitrogen application programs and those previously mentioned. The first standard treatment consisted of 50% of the recommended nitrogen being applied at transplanting and 50% of the recommended nitrogen being applied at layby, to simulate practices currently utilized by growers. The second consisted of 50% of the recommended nitrogen applied at transplanting and 25% applied 2 weeks after transplanting, to evaluate plant response to reduced nitrogen application in a growing season where rainfall is below average. Nitrogen application was initiated after transplanting and was completed between layby and topping, depending upon treatment (Table 3). Possible application timings evaluated were at transplanting, 15 cm, 38 cm (layby), 60 cm, and 120 cm plant height (topping). Application timing corresponded to approximately 0, 2, 4, 6, and 8 weeks after transplanting. Rates of total applied nitrogen were determined by individual growing locations (Table 1). Within each growing location, rates of nitrogen applied were 75% (treatment 2), 100% (treatments 1, 3, 4, 5, and 6), or 125% of the recommended rate (treatments 7 and 8) (Table 3). Treatments were replicated 4 times using a randomized complete block design with factorial treatment arrangement. Individual plots contained 4 rows, each measuring 1.21 m in width by 12.19 m in length. Spacing between individual plants within row was 0.55 m at all locations. Tissue sampling and leaf harvest were performed on the center 2 rows of each plot, with outside rows serving as border rows between treatments.

Treatments were applied using a CO_2-pressurized backpack sprayer with a pressure range of 100–175 kPa depending on application rate and nozzle size. Liquid

Table 1. Soil characteristics, cultivar, transplanting date, and recommended nitrogen rate at individual growing locations.

Location	Soil Series and Taxonomic Class	Soil pH	Variety	Transplanting Date	Base Nitrogen Rate
					----kg/ha-----
BBTRS-12[a]	Goldsboro loamy sand, fine-loamy, siliceous, subactive, thermic AquicPaleudults	6.0	NC 71[e]	April 18, 2012	74
OTRS-12[b]	Helena sandy loam, fine, mixed, semiactive, thermic AquicHapludults	5.9	CC 35[f]	May 14, 2012	80
OTRS-13[c]	Helena sandy loam, fine, mixed, semiactive, thermic AquicHapludults	6.0	CC 27[f]	May 10, 2013	80
UCPRS-13[d]	Norfolk loamy sand, fine-loamy, kaolinitic, thermic TypicKandiudults	5.9	NC 196[e]	April 24, 2013	80

[a] BBTRS-12, Border Belt Tobacco Research Station in 2012.
[b] OTRS-12, Oxford Tobacco Research Station in 2012.
[c] OTRS-13, Oxford Tobacco Research Station in 2013.
[d] UCPRS-13, Upper Coastal Plain Research Station in 2013.
[e] Gold Leaf Seed Company, Hartsville, SC.
[f] Cross Creek Seed Company, Raeford, NC.

urea–ammonium–nitrate (UAN) (28–0–0) supplied 100% of the total nitrogen for all treatments and was applied to each plot on the basis of treatment protocol (Table 3). Nitrogen application before and at layby was soil applied using a simulated soil-directed application technique and then incorporated with a Danish tine rolling cultivator. Nitrogen application after layby occurred directly to the soil surface using a TG-3 or TG-5 full cone nozzle (TeeJet: Spraying Systems Co., Wheaton, IL 60187), depending on application rate. Soil-applied nitrogen at topping was implemented using the same material and equipment. The stalk rundown application method at topping was implemented with a CO_2-pressurized backpack sprayer and a 3-nozzle sucker control boom containing a TG-3, TG-5, TG-3 (TeeJet: Spraying Systems) nozzle arrangement. UAN was mixed with water and applied over the top of the plant at a solution volume of 468 L/ha. Percentage of UAN added to the spray solution was dependent upon the designated nitrogen application rate. Treatments with more than 25% of the total nitrogen applied as stalk rundown were split into two applications to prevent plant injury from excessive nitrogen salt.

Table 2. Monthly rainfall totals at individual growing locations.

Month	BBTRS-12[a]	OTRS-12[b]	OTRS-13[c]	UCPRS-13[d]
	---cm---			
April	5.9	9.9	11.6	6.8
May	22.8	15.6	11.6	7.3
June	5.8	5.7	26.3	25.3
July	20.6	28.1	24.1	12.5
August	36.5	16.5	10.7	11.5
September	10.6	13.8	4.9	12.3
October	11.4	6.3	5.9	8.3
Total	113.6	95.9	95.1	84
Average	80	70	70	70
% above average	41	37	37	20

[a] BBTRS-12, Border Belt Tobacco Research Station in 2012.
[b] OTRS-12, Oxford Tobacco Research Station in 2012.
[c] OTRS-13, Oxford Tobacco Research Station in 2013.
[d] UCPRS-13, Upper Coastal Plain Research Station in 2013.

Tissue samples were collected at layby and at topping to quantify total nitrogen content during the growing season. Green leaf tissue samples were collected from 5 plants within each plot at the third or fourth leaf from the apex of the plant. Samples measured approximately 10 cm wide and 15 cm long. A single 50-g composite sample from all four stalk positions was collected after curing to quantify treatment influence on total alkaloid and reducing-sugar content. After sampling, tissue was dried, ground, and sent to the North Carolina State University Tobacco Analytical Services Lab for nitrogen content, total alkaloid, and reducing-sugar content analysis. Layby and topping tissue sampling occurred approximately 1 week after the corresponding nitrogen treatments were applied. Leaf chlorophyll content was measured using a Konica Minolta SPAD-502 meter (Konica Minolta, Tokyo, Japan). SPAD meter readings occurred on the same day, but before nutrient sample collection for the at-topping

Table 3. Nitrogen application timings, rates, and methods at all growing locations.

Treatment	Nitrogen Application Timing: At Transplanting	2 Weeks after Transplanting[b]	At Layby[c]	2 Weeks after Layby[d]	At Topping[e]	Total Nitrogen	Method of Application[a]
	% of Nitrogen Applied						
1	50	-	50	-	-	100	-
2	50	25	-	-	-	75	-
3	25	-	25	25	25	100	SR[f]
4	25	-	25	25	25	100	SA[g]
5	-	25	25	-	50	100	SR
6	-	25	25	-	50	100	SA
7	50	-	50	-	25	125	SR
8	50	-	50	-	25	125	SA

[a] Method of application refers to nitrogen placement at topping only, before topping nitrogen was soil applied only.
[b] Approximate plant height = 20 cm; application 2 weeks after transplanting.
[c] Approximate plant height = 38 cm; application 4 weeks after transplanting.
[d] Approximate plant height = 50 cm; application 6 weeks after transplanting.
[e] Approximate plant height = 120 cm; application 8 weeks after transplanting.
[f] SR, stalk rundown, applied over the top of the plant.
[g] SA, soil applied, applied to soil surface using simulated drop lines.

interval. In each plot 10 leaves measuring approximately 15 cm long and 10 cm wide were measured using the SPAD meter and then averaged across the entire plot.

Analytical Procedures. *Nitrogen.* Total leaf nitrogen content was analyzed using the procedure of Nelson and Sommers (11) in the North Carolina State University Tobacco Analytical Services Lab in Raleigh, NC. The mMacro-Kjeldahl method was used but with modifications as described by Nelson and Sommers (11), where the sample size was ground to <80-mesh material to improve nitrogen recovery and shorten measurement time for each sample.

Total alkaloids and reducing sugars. Total alkaloid and reducing-sugar content was analyzed using the Perkin-Elmer Autosystem XL gas chromatograph (PerkinElmer, Waltham, MA 02451) procedure in the North Carolina State University Tobacco Analytical Services Laboratory in Raleigh, NC. This procedure quantifies total alkaloid content on the basis of chromatographic peak response at the retention times of alkaloid standards (9).

SPAD measurements. SPAD-502 measurements were conducted using a Minolta chlorophyll meter. SPAD-502 measurements are relative chlorophyll measurements that nondestructively measure red- region transmittance peak of chlorophylls a and b (around 660 nm) of the leaf and calculate a numerical value (SPAD value).

Statistical analysis. Data for crop yield, quality, value, percent nitrogen at layby, percent nitrogen at topping, percent total alkaloids, percent reducing sugars, and SPAD measurements were analyzed in SAS version 9.4 (SAS, Cary, NC 27513). Two separate data analyses were conducted for treatment comparisons. The first analysis compared standard application treatments (treatments 1 and 2) with late-season nitrogen application treatments (treatments 3–8) using a randomized complete block design. The second analysis compared late-season nitrogen applications only (treatments 3–8) using a factorial analysis. For both analyses, all parameters listed were subjected to an analysis of variance using the PROC GLM procedure.

Table 4. Tobacco yield, value, total alkaloid and reducing-sugar content, and nitrogen content at layby and topping across all growing locations for all treatments.[a]

Treatment	Yield	Value	Total Alkaloid	Reducing Sugar	Nitrogen Content AL[b]	Nitrogen Content AT[c]	SPAD Measurement
	kg/ha	$US/ha	%				
1	2,708 a	10,428 a	2.76 bc	14.95 ab	4.17 a	2.93 b	42.93 a
2	2,769 a	10,191 a	2.58 c	16.55 a	4.18 a	2.62 c	41.36 a
3	2,839 a	10,369 a	2.92 ab	14.96 ab	4.03 a	3.23 a	46.17 a
4	2,993 a	10,193 a	2.83 bc	15.47 ab	3.77 a	2.78 bc	43.79 a
5	2,786 a	9,032 a	3.12 a	13.02 c	3.91 a	3.44 a	45.59 a
6	2,854 a	11,060 a	2.95 ab	14.31 bc	4.30 a	2.87 b	44.73 a
7	2,720 a	10,677 a	2.97 ab	14.07 bc	4.06 a	3.22 a	44.59 a
8	2,872 a	10,406 a	2.84 b	14.45 bc	4.15 a	2.87 b	42.84 a

[a] Means followed by the same letter within the same column are not significantly different.
[b] AL, at layby.
[c] AT, at topping.

Table 5. Leaf quality response to nitrogen application at individual growing locations for all treatments.[a]

Treatment	Quality			
	BBTRS-12[b]	OTRS-12[c]	OTRS-13[d]	UCPRS-13[e]
1	91 a	75 a	84 a	81 a
2	91 a	83 a	68 a	80 a
3	89 b	83 a	65 a	87 a
4	81 b	73 a	70 a	79 a
5	72 c	75 a	63 a	86 a
6	83 ab	81 a	86 a	86 a
7	89 ab	86 a	82 a	78 a
8	89 ab	76 a	70 a	82 a

[a] Means followed by the same letter within the same column are not significantly different.
[b] BBTRS-12, Border Belt Tobacco Research Station in 2012.
[c] OTRS-12, Oxford Tobacco Research Station in 2012.
[d] OTRS-13, Oxford Tobacco Research Station in 2013.
[e] UCPRS-13, Upper Coastal Plain Research Station in 2013.

Treatment means were separated using Fisher's Protected LSD at $P \leq 0.05$.

RESULTS AND DISCUSSION

Significant location effects were observed for most parameters, likely due to variability in growing conditions observed at each location. Location-by-treatment interactions were also observed and are reported accordingly.

Analysis I: Late-Season Nitrogen Application Treatments Compared with Standard Treatments. *Yield, value, total alkaloid and reducing-sugar content, nitrogen content at layby and topping, and SPAD measurement.* The effect of late-season nitrogen application on yield, value, leaf chemistry, leaf nitrogen, and SPAD measurement was not significantly different from standard nitrogen application programs (Table 4). In general, nitrogen application occurring through standard early-season treatments resulted in acceptable leaf yield and value but contained reduced nitrogen content at topping and total alkaloids as well as higher sugar content (Table 4). Specifically, total alkaloid content was lowest and reducing-sugar content was highest where 75% of the total recommended nitrogen rate was applied (Table 4). Leaf nitrogen content at topping was lower for the same treatment (Table 4). These results reflect the findings of Elliot and Court (5) who report leaf nitrogen content as being positively correlated with nicotine concentration and negatively correlated with sugar content. Reduced leaf nitrogen and total alkaloid content are most likely due to excessive rainfall, which was experienced in both years of this study (Table 2). Ultimately, results indicate that late-season nitrogen application was acceptable under the growing conditions observed in this study.

Quality. Late-season nitrogen application reduced leaf quality at the BBTRS in 2012; however, quality was not affected by nitrogen application at all other locations (Table 5). Felipe and Long (6) report a leaf-quality reduction as nitrogen application rates increase above recommendation. Late-season nitrogen application may have delayed ripening, ultimately reducing cured leaf quality at this single location.

Analysis II: Comparison of Late-Season Nitrogen Application Treatments. *Yield.* The only factor to significantly affect tobacco yield was nitrogen application method, with soil application yielding 2,902 kg/ha and stalk rundown yielding 2,778 kg/ha. Yield increase from nitrogen application directly to the soil is likely due to greater contact of the effective rooting zone, ultimately leading to a greater possibility of nutrient interception by the rooting system. Alternatively, when the stalk rundown method is utilized, all solution moves to the base of the plant; this area is much smaller in comparison with the continuous band application directly to the soil surface. Furthermore, the volume of solution being applied with the stalk rundown application is approximately 30 mL per plant (on the basis of an application volume of 468 L/ha). Tobacco leaves exhibit very little nutrient absorption through the leaf tissue (3) and, therefore, the critical placement of the solution is at the base of the plant. Slight pooling of the nitrogen solution applied through the stalk rundown

Table 6. Leaf quality response to nitrogen application rate, timing, and method combined over growing locations.[a]

Treatment	Nitrogen Application Timing					Total Nitrogen	Method of Application[b]	Quality Index[c]
	At Transplanting	2 Weeks after Transplanting	At Layby	2 Weeks after Layby	At Topping			
	% of Nitrogen Applied							
3	25	-	25	25	25	100	SR[d]	81 ab
4	25	-	25	25	25	100	SA[e]	76 b
5	-	25	25	-	50	100	SR	74 b
6	-	25	25	-	50	100	SA	84 a
7	50	-	50	-	25	125	SR	83 a
8	50	-	50	-	25	125	SA	79 ab

[a] Means followed by the same letter within the same column are not significantly different.
[b] Method of application refers to nitrogen application at topping, before topping nitrogen was soil applied only.
[c] Quality index is rated on a scale of 1–100, with 100 being of the highest quality.
[d] SR, stalk rundown application, applied over the top of the plant.
[e] SA, soil applied, applied to soil surface using simulated drop lines.

Table 7. Nitrogen application timing and method.

Treatment	Nitrogen Application Timing					Total Nitrogen
	At Transplanting	2 Weeks after Transplanting	At Layby	2 Weeks after Layby	At Topping	
	% Nitrogen Applied					
3	25	-	25	25	25	100
4	25	-	25	25	25	100
5	-	25	25	-	50	100
6	-	25	25	-	50	100
7	50	-	50	-	25	125
8	50	-	50	-	25	125

application was noted; however, most was retained by the plant. After stalk rundown application, any solution remaining on the leaf surface that dries does not reach the effective rooting zone unless facilitated by wash-off through rainfall or irrigation.

Quality. A nitrogen application timing-by-application method interaction was observed; therefore individual treatments are reported (Table 6). Leaf quality was improved when 50% of the total nitrogen was applied directly to the soil surface at topping and when above-recommended rates of total nitrogen were applied through stalk rundown at the same growth stage (Table 6). It has been reported that increasing nitrogen rates above recommendation can result in decreased quality and a delayed ripening (6). This observation was not observed under growing conditions present in this study. It is plausible that the excess rainfall in both years leached nitrogen from the soil profile and therefore normal ripening of the crop was possible. In 2012, late-season rainfall likely removed excess nitrogen from the effective rooting zone. In 2013, because of excessive season-long rainfall, there was likely very little nitrogen available in the soil profile because of leaching, and, as a result the addition of nitrogen late in the season did not add excessive nitrogen to the crop. Late-season applications in 2013 are more accurately described as leaching adjustments, though that was not the primary intention of the study. In a season with average or below-average rainfall, it is likely that treatments applying 50% of the recommended nitrogen at topping would experience a delay in leaf ripening. Assumptions for nitrogen leaching are based on research efforts regarding soil profile nitrogen and excess rainfall (16).

Precaution should be exercised when applying nitrogen as a stalk rundown application as too much nitrogen applied at one time can result in leaf necrosis, which has potential to negatively affect leaf quality. In this study, rates of nitrogen above 25% of the required nitrogen caused leaf damage. Fifteen liters of 28% UAN combined with water for a total of 468 L/ha spray solution was safe for foliar application in the majority of the tests. Thin, stressed tobacco did exhibit minor leaf damage from this application; however, injury was not observed on healthy, vigorous plants.

Value. Crop value was affected by the interaction of nitrogen application timing and method at UCPRS in 2013 (Table 7), most likely due to above-average precipitation and insufficient moisture drainage. In addition, nitrogen applied late in the season above recommended rates did not overcome excessive rainfall. The majority of rainfall at this location occurred between the months of June and September (Table 2), and it is plausible that nitrogen applied later in the growing season was not utilized by the crop. At this location, the 3 highest crop values were observed in treatments receiving the least amount of total applied nitrogen (Table 7). Within these treatments both methods of application were utilized; therefore, no correlation between crop value and nitrogen application method can be readily discerned. Of all treatments, the stalk rundown application at above recommended application rates resulted in the lowest crop value (Table 7). As previously noted, stalk rundown application of nitrogen resulted in lower leaf yields when compared with direct soil application. Reduced leaf yield often results in lower crop value.

Total alkaloids. Nitrogen application did not affect total alkaloid content (data not shown). Treatment averages for total alkaloid content ranged from 2.83 to 3.12%, which fall within the acceptable range for total alkaloids as noted by Chaplin and Miner (2).

Reducing sugars. Nitrogen application timing affected reducing-sugar content (Table 8). Treatments receiving 50% of the total nitrogen at topping resulted in the lowest reducing-sugar content (Table 8). Initiation of starch accumulation begins once nicotine and protein synthesis have terminated (5). Termination of protein synthesis occurs in a nitrogen-deficient system or when nitrogen availability ceases for plant uptake (15). Treatments with a portion of total nitrogen applied at transplanting had less nitrogen applied later in the season, allowing for earlier initiation of starch accumulation (Table 8). This is the most likely cause for the higher reducing sugar when compared with treatments that did not have nitrogen applied until 2 weeks after transplanting (Table 8). Regardless of treatment, all averages for total reducing-sugar content fell within the percentage range of 1,500 tobacco cultivars that were evaluated at a single environment grown under similar cultural practices (2).

Leaf nitrogen content at layby. Leaf nitrogen content at layby response to nitrogen application timing was different at OTRS-13 and UCPRS-13 (Table 9). At OTRS-13 leaf nitrogen was lowest when nitrogen was

Table 7. Extended: Crop value response at individual growing locations.[a]

Treatment	Method of Application	Location			
		BBTRS-12[d]	OTRS-12[e]	OTRS-13[f]	UCPRS-13[g]
3	SR[b]	13,271 a	12,341 a	9,987 a	5,881 a
4	SA[c]	11,547 a	12,956 a	10,731 a	5,545 ab
5	SR	10,201 a	11,941 a	8,925 a	5,064 abc
6	SA	12,978 a	12,708 a	14,100 a	4,461 bc
7	SR	12,829 a	12,732 a	13,379 a	3,768 c
8	SA	13,911 a	12,303 a	10,875 a	4,537 bc

[a] Means followed by the same letter within the same column are not significantly different.
[b] SR, stalk rundown, applied over the top of the plant.
[c] SA, soil applied, applied to soil surface using simulated drop lines.
[d] BBTRS-12, Border Belt Tobacco Research Station in 2012.
[e] OTRS-12, Oxford Tobacco Research Station in 2012.
[f] OTRS-13, Oxford Tobacco Research Station in 2013.
[g] UCPRS-13, Upper Coastal Plain Research Station in 2013.

split-applied at transplanting and layby because of high early-season rainfall (Tables 2, 9). The opposite was observed at UCPRS-13, where leaf nitrogen content was lowest when nitrogen application occurred 2 weeks after transplanting and at layby, indicating that sufficient nutrient accumulation had not yet occurred (Table 9).

Leaf nitrogen content at topping. The response of leaf nitrogen content at topping was different at 2 of the 4 growing locations (Table 10). The stalk rundown method resulted in higher leaf nitrogen content at topping than the soil-applied method at OTRS-12 and OTRS-13 (Table 10). Within each location, percent leaf nitrogen content varied only slightly, which is most likely due to the lack of extreme nitrogen rate differences between the treatments. Previous research efforts have demonstrated that foliar uptake of nitrogen in tobacco is not an effective means of fertilization (3); in addition, there are likely other reasons for this response. One plausible reason is that by facilitating stalk rundown of the nitrogen solution to the base of the plant, root interception and absorption may occur faster than with a direct soil application. Additionally, nitrogen residue from the stalk rundown application could have remained on the leaf surface, resulting in increased nitrogen percentage of the leaf when quantified in the laboratory.

SPAD measurements. SPAD measurements were different at the OTRS-12 and UCPRS-13 because of nitrogen application method (Table 10). The stalk rundown application method resulted in higher SPAD measurements at both locations (Table 10). With SPAD readings being indicative of chlorophyll content, higher measurements are likely correlated to the higher leaf nitrogen content at topping as both of these parameters were measured on the same day from the same leaf position. In general, stalk rundown application of nitrogen also resulted in higher leaf nitrogen content at topping (Table 10).

CONCLUSION

Flue-cured tobacco produced with late-season nitrogen applications resulted in similar agronomic and chemical composition to leaf produced under typical nitrogen application programs. The similarities observed between the two approaches to nitrogen management indicate that late-season nitrogen application is an option for tobacco producers in the United States; however, growers are encouraged to exercise caution when considering these management practices. Within late-season nitrogen application evaluations, nitrogen application timing and method affected agronomic and chemical measurements. Soil-applied nitrogen resulted in improved leaf yield and quality, likely due to prolonged nitrogen availability during periods of excessive rainfall. Nitrogen application through stalk rundown provided a quicker response when assessing leaf tissue nitrogen content and SPAD measurements. Results indicated that late-season soil application of nitrogen as a leaching adjustment is acceptable and can potentially increase leaf yield in seasons with greater-than-normal precipitation. Alternatively, stalk rundown

Table 8. Reducing-sugar content in response to nitrogen application timing combined across all growing locations[a]

Treatments[b]	Nitrogen Application Timing					Total Nitrogen	Reducing Sugars
	At Transplanting	2 Weeks after Transplanting	At Layby	2 Weeks after Layby	At Topping		
	% Nitrogen Applied						%
3, 4	25	-	25	25	25	100	15.22 a
5, 6	-	25	25	-	50	100	13.66 b
7, 8	50	-	50	-	25	125	14.26 ab

[a] Means followed by the same letter within the same column are not significantly different.
[b] Treatments are combined on the basis of similarities in nitrogen application timing.

Table 9. **Leaf nitrogen content at layby in response to nitrogen application timing at individual growing locations.[a]**

Treatments[b]	Nitrogen Application Timing: At Transplaning	2 Weeks after Transplanting	At Layby	2 Weeks after Layby	At Topping	Total Nitrogen	Leaf Nitrogen Content at Layby: BBTRS-12[c]	OTRS-12[d]	OTRS-13[e]	UCPRS-13[f]
	% nitrogen applied						%			
3, 4	25	-	25	25	25	100	3.75 a	4.04 a	3.72 b	4.11 a
5, 6	-	25	25	-	50	100	3.72 a	4.78 a	4.34 a	3.59 b
7, 8	50	-	50	-	25	125	3.61 a	4.04 a	4.63 a	4.15 a

[a] Means followed by the same letter within the same column are not significantly different.
[b] Treatments are combined on the basis of similarities in nitrogen application timing,
[c] BBTRS-12, Border Belt Tobacco Research Station in 2012.
[d] OTRS-12, Oxford Tobacco Research Station in 2012.
[e] OTRS-13,; Oxford Tobacco Research Station in 2013.
[f] UCPRS-13; Upper Coastal Plain Research Station in 2013.

application of nitrogen is suitable for increasing tobacco leaf greenness, thus promoting leaf holdability in the field. This practice is likely beneficial to producers experiencing issues related to curing capacity and availability of curing barn space. During growing seasons with excessive rainfall curing barn space becomes problematic because of expedited leaf ripening through the loss of soil nitrogen. It is in this scenario that a rapid uptake of nitrogen by the tobacco plant could potentially alleviate these issues, allowing for a more gradual harvesting and curing process.

Research from the 4 locations in this study provided excellent representation of the growing conditions experienced in North Carolina during the 2012 and 2013 seasons. Rainfall was above average late in the 2012 season and above average earlier in the 2013 season; both scenarios are believed to have affected soil nitrogen availability due to leaching. On the basis of previous research efforts (3,13), it can be expected that if less rainfall had occurred in both growing seasons, differences in yield, quality, and value may have been observed. Specifically, nitrogen programs delivering 50% of the total nitrogen at topping or greater-than-recommended rates of nitrogen would likely have resulted in a reduction of leaf quality due to prolonged nitrogen assimilation. Ultimately, leaf quality and curing-related issues were not observed in this study because of excessive rainfall in 2012 and 2013; however, additional research is needed to evaluate the impact of late-season nitrogen applications during normal to dry growing seasons.

The selection of liquid fertilizer sources allows for increased ease in nutrient application and reduced input cost for nitrogen fertilizer materials. The fertilizer source and application methods selected for this study are easily obtainable and practical to implement for the majority of growers in the tobacco-producing regions of the United States. Despite favorable results observed in this study, producers should be aware of the issues associated with stalk rundown application. Nitrogen, when applied at rates similar to those in this study, delivers a large quantity of salt to the plant, which can result in significant injury. Growers should add no more than 20 kg/ha of nitrogen to water in a 468 L solution to reduce injury potential. To further alleviate injury potential, a reduced amount of fertilizer (11–17 kg N/ha) could be utilized in multiple applications. In addition, stalk rundown-applied nitrogen was not tank mixed with a fatty alcohol suckercide. This practice is generally discouraged as the combination of the two materials is likely to result in significant leaf injury.

Ultimately, the implementation of late-season nitrogen application programs provide management options for U.S. flue-cured tobacco producers. These practices allow farmers to make nitrogen application decisions on the basis of current weather conditions as well as plant growth stage. In seasons marked by below-average rainfall the risk of overfertilization is greatly

Table 10. **Leaf nitrogen content at topping and SPAD measurement response to nitrogen application method at individual growing locations.[a]**

Application Method	Leaf Nitrogen Content at Topping: BBTRS-12[b]	OTRS-12[c]	OTRS-13[d]	UCPRS-13[e]	SPAD Measurements: BBTRS-12	OTRS-12	OTRS-13	UCPRS-13
	%							
Stalk rundown	2.68 a	4.90 a	3.63 a	2.01 a	44.66 a	46.13 a	46.20 a	44.60 a
Soil applied	2.50 a	4.00 b	3.14 b	1.77 a	45.00 a	44.28 b	47.31 a	38.88 b

[a] Means followed by the same letter within the same column are not significantly different.
[b] BBTRS-12, Border Belt Tobacco Research Station in 2012.
[c] OTRS-12, Oxford Tobacco Research Station in 2012.
[d] OTRS-13, Oxford Tobacco Research Station in 2013.
[e] UCPRS-13, Upper Coastal Plain Research Station in 2013.

reduced, thus allowing for a normal ripening process of the leaf. Alternatively, in seasons characterized by excessive rainfall, such as those in this study, the opportunity for late-season nitrogen adjustments allows for increased crop yield and more favorable leaf chemistry. It is recommended that producers approach both scenarios with sufficient consideration.

LITERATURE CITED

1. Bowman DT, Tart AG, Wernsman EA, Corbin TC. 1988. Revised North Carolina grade index for flue-cured tobacco. Tobacco Science 32:39–40.

2. Chaplin JF, Miner GS. 1980. Production factors affecting chemical components of the tobacco leaf. Recent Advances in Tobacco Science 6:3–63.

3. Collins WK, Hawks SN Jr. 1993. Fertilization. Pages 97–140. in: Principles of flue-cured tobacco production (3rd ed.). W.K. Collins and S.N. Hawks Jr., Raleigh, NC.

4. Drake MP. 2014. Evaluation of nitrogen application timings on yield, quality, and sucker control [thesis]. Raleigh (NC): North Carolina State University. 95 p. Available from: NCSU Libraries, Raleigh, NC; 9522. Available.

5. Elliot JM, Court WA. 1978. The effects of applied nitrogen on certain properties of flue-cured tobacco and smoke characteristics of cigarettes. Tobacco Science 22:54–58.

6. Felipe EE, Long RC. 1988. Management of flue-cured tobacco grown with excess nitrogen. Tobacco Science 32:53–56.

7. Fisher LR, editor. 2014. North Carolina State University: Flue-cured tobacco guide 2014. AG-187. North Carolina Cooperative Extension, Raleigh, NC.

8. Flower KC. 1999. Field practices. Pages 76–103. in: Tobacco: Production, chemistry, and technology. D.L. Davis and M.T. Nielsen, eds. Blackwell Science, London.

9. Lewis RS, Parker RG, Danehower DA, Andres K, Jack AM, Whitely DS, Bush LP. 2012. Impact of alleles at the *yellow burley (yb)* loci and nitrogen fertilization rate on nitrogen utilization efficiency and tobacco-specific nitrosamines (TSNA) formation in air-cured tobacco. Journal of Agricultural and Food Chemistry 60:6454–6461.

10. McCants CB, Woltz WG. 1967. Growth and mineral nutrition of tobacco. Advances in Agronomy 19:211–265.

11. Nelson DW, Sommers LE. 1973. Determination of total nitrogen in plant material. Agronomy Journal 65:109–112.

12. Parker RG. 2009. Evaluation of nitrogen sources and rates on yield and quality of flue-cured tobacco [dissertation]. Raleigh (NC): North Carolina State University. 78 p. Available from: NCSU Libraries, Raleigh, NC; 317128318. Available.

13. Peedin GF. 1999. Production practices: Flue-cured tobacco. Pages 104–142. in: Tobacco: Production, chemistry, and technology. D.L. Davis and M.T. Nielsen, eds. Blackwell Science, London.

14. Raper CD, McCants CB. 1966. Nutrient accumulation in flue-cured tobacco. Tobacco Science 10:109.

15. Tso TC. 1990a. Soil and fertilizer. Pages 75–82. in: Production, physiology, and biochemistry of tobacco plant. Ideals, Inc, Beltsville, MD.

16. Vann MC, Smith WD. 2014. Managing nutrients. Pages 62–77. in: North Carolina State University: Flue-cured tobacco guide 2014. AG-187. Revised ed. North Carolina Cooperative Extension Service, Raleigh, NC.

17. Weybrew JA, Woltz WG, Monroe RJ. 1984. Harvesting and curing flue-cured tobacco: The effects of ripeness at harvest and duration of yellowing on yield, physical characteristics, chemical composition, and smoker preference. NC Agricultural Technical Research Technical Bulletin 275. North Carolina State University. Raleigh, NC.