Cotton Nitrogen Management in a High-Residue Conservation System: Cover Crop Fertilization

M. S. Reiter*
Virginia Polytechnic Inst. and State Univ.
Eastern Shore Agric. Research and Ext. Center
33446 Research Dr.
Painter, VA 23420

D. W. Reeves
USDA-ARS
J. Phil Campbell Sr. Natural Resource Conserv. Center
1420 Experiment Station Rd.
Watkinsville, GA 30677

C. H. Burmester
Auburn Univ.
Agronomy and Soils Dep.
202 Funchess Hall
Auburn University, AL 36849

H. A. Torbert
USDA-ARS
National Soil Dynamics Lab.
411 South Donahue Dr.
Auburn, AL 36832

Nitrogen is required for adequate residue production from cereal cover crops used in no-till cotton (*Gossypium hirsutum* L.) production, but residues can immobilize N needed by cotton. We conducted a 3-yr field study on a Decatur silt loam (clayey, kaolinitic, thermic Rhodic Paleudult) in northern Alabama to test N fertilizer practices for cotton grown with a rye (*Secale cereale* L.) cover crop and conservation tillage. Nitrogen rates applied to the rye cover crop were 0, 34, and 67 kg N ha^{-1} and cotton N rates were 0, 45, 90, and 135 kg N ha^{-1}. Additionally, ^{15}N microplots were established in cover crop N treatments of 34 kg N ha^{-1} and in cotton treatments of 90 kg N ha^{-1}. Data collected included cover crop aerial biomass, cover crop C/N ratios, cotton leaf N at first flower, lint yield, lint quality, and ^{15}N in plant and soil samples. Cotton grown in unfertilized rye treatments needed 57 to 60% (38–40 kg N ha^{-1}) more N to maximize yields above median conventional tillage N recommendations (67 kg N ha^{-1}). Cover crop N rates of 67 kg N ha^{-1} maximized cover crop biomass production for soil protection and soil organic matter aggradation. If the cover crop was fertilized, minimum cotton N applications of 70 and 76 kg N ha^{-1} were needed for economic optimum and maximum lint yield, respectively. We speculate that cotton N rates may be decreased in the future as new N and C pool equilibria are reached.

Abbreviations: FUE, fertilizer nitrogen use efficiency; SOM, soil organic matter.

SOIL FERTILITY & PLANT NUTRITION

Nearly 87,660 ha of Alabama's 241,525 ha of cotton was grown in the Tennessee Valley region of Alabama in 2002, ensuring this area as a vital player in the Cotton Belt (Conservation Technology Information Center, 2003, available through NRCS offices). A historical use of conventional tillage in this area has led to >100 yr of soil degradation from erosion and loss of organic matter (Schwab et al., 2002). These detrimental practices resulted in high soil losses (>35.8 t soil ha^{-1} yr^{-1}), which were the highest in the state in the late 1980s (Yoo et al., 1989).

As a result of an aggressive education, research, and technology effort, nearly 70% of farmers in the Tennessee Valley region of Alabama are currently using conservation tillage systems (Conservation Technology Information Center, 2003, available through NRCS offices), with many utilizing high-residue cereal cover crops (>4500 kg residue ha^{-1}). Compared for tillage implement, tillage depth, and a winter cover crop, rye was found to be the most critical factor in increasing cotton yields in the Tennessee Valley of Alabama (Raper et al., 2000). Erosion control increases as the amount of cover crop residue increases, and high-residue cover crops can increase soil C levels. Increasing levels of organic C will reduce CO_2 concentrations in the atmosphere, improve soil quality, and ultimately increase agronomic production potential (Motta, 2002; Causarano et al., 2006).

Although high-biomass cover crops can help solve erosion problems and contribute valuable C to the soil, they can cause problems with crop management. Cover crops were shown to reduce cotton yields by depleting available soil water in Alabama studies; however, the reduction in cotton yield was limited to droughty springs and summers (Keisling et al., 1994). Field studies by Bronson et al. (2001) showed no cotton yield differences between conventional and conservation tillage cover crop systems in Texas during a water use study. Ultimately, any negative cover crop water mining effects may

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*Corresponding author (mreiter@vt.edu).

be reduced by increased rainfall infiltration and reduced evaporation losses (Reeves, 1994).

Nitrogen management is often cited as a primary problem when cereal cover crops are introduced into crop rotations, and the timing of desiccation is often considered (Reeves, 1994). A young crop of rye killed early in the spring will have low biomass production but will have a higher N concentration and low C/N ratio (Huntington et al., 1985). Conversely, delaying desiccation of rye until it approaches physiological maturity, which is needed for soil erosion control and to increase soil organic C inputs, will greatly increase biomass but will result in a low N content and high C/N ratio (Huntington et al., 1985; Wagger, 1989). High C/N residues can immobilize available soil N and create a need for higher rates of N fertilizer for crops planted into these residues (Wagger, 1989; Reeves, 1994; Hutchinson et al., 1995). Wagger (1989) terminated rye at 2-wk intervals before corn (*Zea mays* L.) planting, which occurred in mid-April and early May for two locations in North Carolina, and found that allowing rye to grow 2 wk beyond full anthesis before desiccation increased biomass by 29%, from an average of 5900 to 8240 kg residue ha^{-1}. Total N in the residue increased by only 14%, resulting in a higher C/N ratio. This study showed that rye desiccated late had less N release than earlier killed rye, supplying minimal amounts of N into the system. Sixteen weeks after kill, early-killed rye contributed about 33.5 kg N ha^{-1} to the system while late-killed rye added only 20.5 kg N ha^{-1}. The late-killed rye took longer to decompose, offering more ground cover and protection (Wagger, 1989), but probably immobilized N in the system.

When cultural practices, such as eliminating tillage and growing high-biomass-producing cover crops, increase soil C, there is a corresponding increase in the soil organic N pool. To accommodate the need for more soil N, higher fertilizer N rates may be needed for subsequent crops until the N and C pools reach a new equilibrium. Several researchers (Wagger, 1989; Reeves, 1994; Hutchinson et al., 1995) have reported that higher than normally recommended rates of N fertilizer are needed in systems where organic C levels are being increased. Hutchinson et al. (1995) reported that 34% more N (118 kg N ha^{-1} total) was needed by cotton in Louisiana when a winter wheat (*Triticum aestivum* L.) cover crop was used compared with volunteer native vegetation on a fallow winter field.

There are indications that when a new equilibrium is reached, N rates higher than normally expected may not be needed as microbial activity and N mineralization will proportionally increase (Salinas-Garcia et al., 1997; Dinnes et al., 2003). It was also reported that incorporation of cover crops with wide C/N ratios did not immobilize N (Bauer et al., 1993). Whether or not residues with wide C/N ratios result in net N immobilization or mineralization depends on many factors, such as stable soil C concentrations, cover crop age, N in the cover crop, and various management practices. Virtually no research has considered if N fertilizer applied to cereal cover crops will be available to subsequent cotton crops. The objective of this study was to determine if N applied to cover crops would be plant available and assimilated by cotton in subsequent growing seasons for southeastern U.S. cropping systems. We hypothesized that N may be added to cover crops to increase rye biomass and lower C/N ratios. Lower C/N ratios would facilitate N mineralization during the subsequent cotton growing season, thereby reducing cotton N rate requirements.

MATERIALS AND METHODS

Site Description

This 3-yr (2000–2002 cotton growing seasons) field experiment was initiated in November 1999 at the Tennessee Valley Research and Extension Center of the Alabama Agricultural Experiment Station, in Belle Mina, AL (34°41′00″ N, 86°53′02″ W, elevation 157 m), with planting of a rye cover crop for the 2000 cotton crop. The soil was predominantly a Decatur silt loam and was historically in conventionally tilled monoculture cotton production.

The experimental design was a strip plot with four replications. Nitrogen rates for the cover crops (0, 34, and 67 kg N ha^{-1}) were stripped horizontally (east–west) across the field while cotton N rates (0, 45, 90, and 135 kg N ha^{-1}) were stripped vertically (north–south), effectively giving 3 cover crop N rates × 4 cotton N rates = 12 N treatment combinations.

Cultural Practices

Phosphorous, K, and lime applied before planting the fall cover crop were based on Auburn University Soil test recommendations (Adams and Mitchell, 2000). Each fall, plots were noninversion deep tilled to a 46-cm depth using a Paratill bent-leg subsoiler (Bigham Brothers, Lubbock, TX) immediately following the planting of the rye cover crop (Schwab et al., 2002). Equipment used was guided with a Trimble AgGPS Autopilot automatic steering system (Trimble, Sunnyvale, CA), with centimeter-level precision, which reduced equipment-induced compaction near the cotton row and facilitated N applications.

The rye used was 'Elbon', and SureGrow 125 BG/RR (2000 and 2001) and SureGrow 215 BG/RR (2002) cotton were used. Rye was planted in October to November of 1999, 2000, and 2001 (Table 1) with a conventional grain drill at a rate of 112 kg seed ha^{-1} and terminated at anthesis (late March 2000 and mid-April of 2001 and 2002) using glyphosate [*N*-(phosphonomethyl)glycine] at the labeled rate (1.12 kg isopropylamine salt ha^{-1}). A roller/crimper was then used to roll down the cover crop in the same direction as the cotton was planted (Ashford and Reeves, 2003). Cotton was planted in early May using a four-row unit vacuum planter set on 102-cm rows at a seeding rate of 16 seeds m^{-1}. All cotton production

Table 1. Cultural practices of a high-residue cover crop N efficiency experiment in a conservation tillage cotton production system in the Tennessee Valley of Alabama.

Operation	Cotton growing season		
	2000	2001	2002
Plant rye cover crop	19 Oct. (1999)	14 Nov. (2000)	30 Oct. (2001)
Apply N to cover crop	10 Feb.	1 Mar.	14 Feb.
Terminate cover crop	29 Mar.	12 Apr.	10 Apr.
Plant cotton	4 May	4 May	9 May
Apply N to cotton	10 May	4 May	15 May
Defoliate cotton	13 Sept.	13 Sept.	20 Sept.
Harvest cotton	28 Sept.	10 Oct.	9 Oct.
Establish rye ^{15}N microplot	10 Feb.	1 Mar.	14 Feb.
Establish cotton ^{15}N microplot	12 May†	4 May	15 May

† Microplot had misapplication of ^{15}N and was disregarded.

practices were followed as outlined by the Alabama Cooperative Extension System.

Nitrogen treatments (NH_4NO_3, 340 g N kg^{-1}) were applied to rye in February 2000, March 2001, and February 2002 at approximately the five-tiller stage using a drop spreader equipped for broadcast applications (Table 1). Nitrogen treatments (NH_4NO_3, 340 g N kg^{-1}) were applied to cotton soon after planting, using the same drop spreader. To account for alley border effects, 76 cm was cut off the ends of each plot using a rotary mower before harvest. The center two rows from each plot were harvested with a spindle picker equipped with a sacking unit.

Sample Analysis

Before termination, aboveground cover crop biomass was sampled by collecting two 0.25-m^2 samples from each plot. Residue was dried at 55°C until all moisture was removed and then weighed to determine dry matter per hectare. Total C and N were determined by dry combustion using a Fisons 1500 NCS nitrogen/carbon analyzer (Fisons Instruments, Beverly, MA) (Jones, 2001). At first flower, 25 cotton leaf blades per plot were collected and dried for leaf N concentration determination by dry combustion using the Fisons 1500 NCS nitrogen/carbon analyzer (Jones, 2001). Harvested cotton was subsampled and ginning percentage was determined, using a 10-saw microgin, before the cotton was sent to the USDA classing office (USDA, Pelham, AL) for high-volume instrumentation analysis.

Nitrogen Isotope Tracer

Microplots were established adjacent to each other in the same strip-plot treatment each year, with cover crop N treatments of 34 kg N ha^{-1} and cotton treatments of 90 kg N ha^{-1}. The 0-N treatments provided heavy isotope (^{15}N) background levels. Microplots were established in 2000, 2001, and 2002 with each rye and cotton fertilizer N application, thereby establishing two new microplots per strip plot per year (2 crops × 3 yr = 6 microplots per strip plot). The 2000 cotton microplot was disregarded altogether because ^{15}N fertilizer was misapplied at microplot establishment. To establish the microplot, plastic was used to cover a 406- by 152-cm area during N applications with the drop spreader. After application, the plastic was carefully removed so NH_4NO_3 would not spill onto the untreated area. Premeasured ^{15}N-enriched NH_4NO_3 was used, which contained 2.0 atom % ^{15}N, and was mixed with fine sand to facilitate application. A divider of four equal areas was placed over the microplot and the treatment mixture was equally spread over the area. The plot was then marked with stakes and fertilized with regular NH_4NO_3 at each subsequent treatment for the duration of the test.

Whole-plant aboveground subsamples were collected across the entire ^{15}N microplot and in the 0-N treatment main plots for rye. Total dry matter was calculated from two 0.25-m^2 plant samples taken outside of the microplot but within the same strip plot to avoid removing excess vegetation that contained ^{15}N-labeled fertilizer. Cotton plant samples for ^{15}N determination were collected from 1 m of the center two cotton harvest rows at 20% open boll near peak N plant accumulation (approximately 125 d after planting) (Mullins and Burmester, 1990). Rye and cotton samples were dried at 55°C until all moisture was removed. Cotton samples were partitioned into vegetative (stems and leaves) and reproductive (seeds and bracts) plant parts and weighed. These parts were then ground and sent to Isotope Services, Inc. (Los Alamos, NM), for total N (TN) and $^{15}N/^{14}N$ ratio determination.

Soil samples were taken to a depth of 46 cm immediately following cotton harvest in each established microplot and the 0-N control. Any residue left on the soil surface was mixed in with soil samples when probing randomly within the microplot. Soil samples were then air dried, ground to pass a 2-mm screen, and sent for ^{15}N analysis to Isotope Services for TN and $^{15}N/^{14}N$ ratio determination. They were also analyzed by dry combustion on a TruSpec Elemental Determinator Carbon/Nitrogen (LECO Corp., St. Joseph, MI) to determine soil C/N ratios (Jones, 2001).

For each microplot during the test, residual N was determined in plant residue and soils as: total N uptake = $[(TN \times {}^{15}N_{sample}) - (TN \times {}^{15}N_{background})]/({}^{15}N_{fertilizer} - {}^{15}N_{background})$, where total N uptake is total N utilized from enriched ^{15}N fertilization, TN is the combination of all N forms in the sample, $^{15}N_{sample}$ is the amount of heavy isotope in the treated plot, $^{15}N_{background}$ is the amount of heavy isotope found naturally in the 0-N check plot, and $^{15}N_{fertilizer}$ is the percentage of heavy isotope in the total fertilizer (2.0 atom % ^{15}N) (Hauck and Bremner, 1976; Torbert et al., 1992). Fertilizer N use efficiency (FUE) was calculated as: FUE = (total N uptake/N applied)100, where FUE is the ratio of N taken up by the plant from fertilization, total N uptake is TN utilized from enriched ^{15}N fertilization (or plant TN uptake – no-fertilizer treatment), and N applied is the rate of fertilizer applied (34 kg N ha^{-1} for rye and 90 kg N ha^{-1} for cotton).

Statistics

Data were analyzed with general linear model procedures (GLM) and means were separated using Fisher's protected LSD using SAS (SAS Institute, 2001). Regression equations were developed utilizing simple linear and nonlinear regression (REG). Only the highest order significant model is presented. Nitrogen rates necessary for maximum cotton yield were found by setting the first derivative of the quadratic equation to 0. Maximum economic yield was calculated by setting the quadratic equation equal to a N fertilizer/lint price ratio of 0.70, as discussed by Bronson et al. (2001) (US\$0.82 kg^{-1} N and US\$1.17 kg^{-1} lint, 10-yr price average; USDA Economic Research Service, 2007). The model was tested across years using procedures described by McIntosh (1983). A significance level of $P \leq 0.10$ was established a priori.

RESULTS AND DISCUSSION

Cover Crop Biomass

Cover crop aerial biomass varied from 790 to 7930 kg residue ha^{-1} during 2000 to 2002. Averaged across years, cover crop biomass was quadratically related to cotton lint yield, suggesting a weak but positive impact of residue quantity on lint yield (lint yield = $694.18 + 0.16x - 0.000014x^2$, R^2 = 0.31). Using the quadratic model, cotton yield increased to 5714 kg cover crop biomass ha^{-1} and then decreased, possibly due to limiting N or other problems associated with high-residue cover crops (Reeves, 1994). For instance, cotton leaf N status at first flower indicated a N deficiency in the study's first 2 yr after conservation tillage was initiated.

Cotton N applications did not precede the initial rye cover crop planted in fall 1999; however, there was a significant cover crop rate main effect in 2000 and 2002 (Table 2). The highest cover crop N rate of 67 kg N ha^{-1} provided the most cover crop aerial biomass for soil protection in both years compared with lower N treatments. Cotton N applications affected cover crop aerial biomass in 2001, with a significant cover crop N rate × cotton N rate

Table 2. Cover crop N rate main effect on rye aerial biomass production (2000 and 2002), N content, and C/N ratios and interaction of cover crop N rate (0, 34, 67 kg N ha^{-1}) × cotton N rate (0, 45, 90, and 135 kg N ha^{-1}) on rye aerial biomass (2001) for a high-residue conservation tillage system located in the Tennessee Valley of Alabama in 2000, 2001, and 2002.

Rye cover crop N rate	Biomass production		N content†	C/N ratio†	Biomass production, 2001‡			
	2000	2002			0 kg N	45 kg N	90 kg N	135 kg N
kg N ha^{-1}	— kg biomass ha^{-1} —		g N kg^{-1}		kg biomass ha^{-1}			
0	4695	2687	16.1	27:1	905	790	1220	1135
34	5106	4480	17.5	25:1	2140	1710	1918	2415
67	7474	5436	21.0	21:1	2105	2640	2655	2355
LSD(0.10)§	788	310	1.2	1.8				

† Averaged across cotton N application rates and years.

‡ 2001 LSD(0.10) for cover crop rate at same cotton rate (down) within year = 552 kg biomass ha^{-1}; for cotton rate at same cover crop rate (across) within year = 553 kg biomass ha^{-1}.

§ LSD(0.10) within same column.

interaction (Table 2). Cover crop applications of 34 kg N ha^{-1} increased cover crop biomass over 0-N treatments across all residual cotton N rates; however, cover crop applications of 67 kg N ha^{-1} only increased cover crop biomass at residual cotton N treatments of 45 and 90 kg N ha^{-1} (Table 2). Overall, cover crop biomass in 2001 was less than in 2000 and 2002 (Table 2). Fewer growing degree units were accumulated due to a cool autumn and winter, calculated with a 4.4°C base (Nuttonson, 1958) (Fig. 1).

Cover Crop Carbon/Nitrogen Ratio

Carbon/nitrogen ratios were dependent on N application rates and the response was similar for all 3 yr. Averaged across years, cover crop biomass C/N ratios ranged from 21:1 (21.8 g N kg^{-1} tissue for 67 kg N ha^{-1} on rye and 0 N on cotton) to 28:1 (15.4 g N kg^{-1} tissue for the 0-N control), which could result in mineralization or immobilization of N during the season, respectively. The cover crop receiving 67 kg N ha^{-1} had a lower C/N ratio and higher N content than rye receiving 0 or 34 kg N ha^{-1} (Table 2), averaged across cotton N rates and years. A low C/N ratio, with high levels of tissue N, should facilitate residue decomposition and release inorganic N for crop use during the cotton growing season (Ocio et al., 1991; Bremer and van Kessel, 1992).

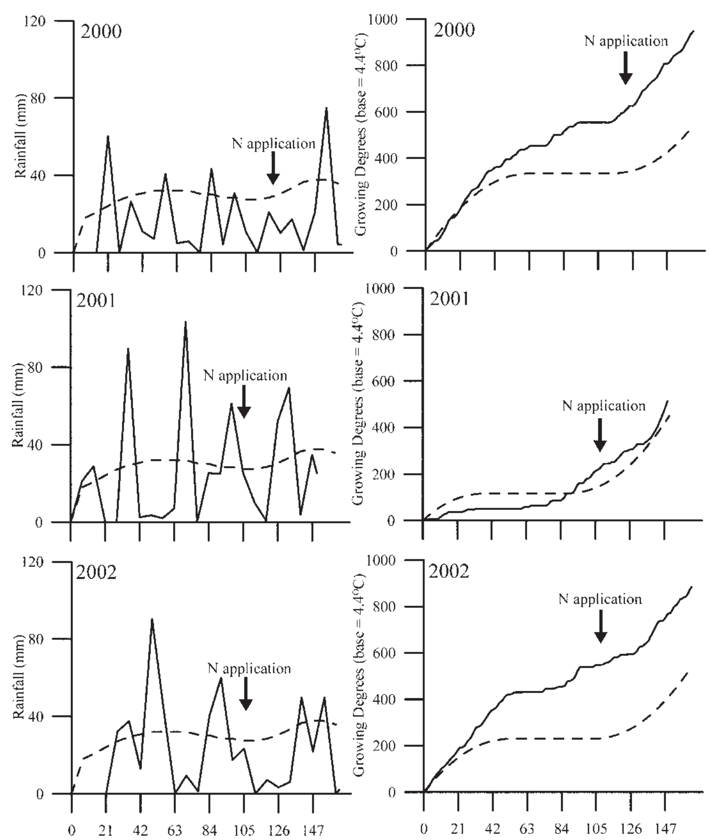

Fig. 1. Precipitation and growing degree heat unit (base = 4.4°C) patterns from planting to termination of rye cover crop in the Tennessee Valley of Alabama in 2000, 2001, and 2002: yearly pattern (solid line) and 30-yr average (broken line).

Fertilizer Nitrogen Use Efficiency

Fertilizer N use efficiencies calculated from ^{15}N microplots showed varying results across years (Tables 3 and 4). In the first year of ^{15}N fertilizer application (Tables 1 and 3) (established with 2000 cover crop), 53% (18.0 kg N) of the N fertilizer applied was assimilated by the cover crop. The following cotton crop utilized 30% (10.2 kg N) of the N applied to the cover crop. Nitrogen available to the cotton from the rye application could have been derived from residual mineral N since leaching was limited due to low rainfall (Fig. 2), from mineralized N from cover crop organic matter, or from remineralized N from soil organic matter (SOM). In 2001, the cover crop utilized only 3% (0.9 kg N) from the 2000 cover crop fertilization, while cotton utilized 8% (2.8 kg N) (Table 3). Although 21.2 kg fertilizer N ha^{-1} remained in the soil from the 2000 cover crop fertilization with a normal soil C/N ratio in November 2000 (10:1) (Brady, 1974), low uptake of ^{15}N fertilizer can be explained by ^{15}N fertilizer being immobilized and nonfertilizer organic N being mineralized. These findings are similar to the priming effect in other studies using corn and legumes as cover crops (Reeves et al., 1993; Torbert et al., 1996). A "true" priming effect occurs when N additions promote mineralization of organic N, supplementing fertilizer N (Jenkinson et al., 1985); however, these added N interactions are often "apparent" and the result of isotopic substitution. No statistically significant N from the initial 2000 cover crop or cotton fertilization was found in the cover crop during the 2002 growing season; however, 45% (15.5 kg N ha^{-1}) of fertilizer N was still immobolized in the soil 3 yr after the initial application.

Cover crop N FUE was lower with the 2001 N application than the 2000 cover crop fertilization (37 vs. 53% for

2000 and 2001, respectively; Tables 1 and 3). The cover crop assimilated 12.6 kg of the 34 kg N ha^{-1} applied in 2001. High rainfall (Fig. 1) during the winter of 2001 probably increased N losses due to denitrification and leaching compared with 2000. This decreased efficiency also corresponds to slightly higher than normal soil C/N ratios in the fall of 2001 (13:1) and low cover crop biomass production levels, which was probably due to a cold winter (Fig. 1) and shorter growing season (Table 1). Cotton in 2001 utilized 15% (5.2 kg N) of N applied to the 2001 cover crop, half of the amount recovered by cotton from cover crop N applications in 2000. Measurements of residual soil ^{15}N in fall 2001 indicated that 27.2 kg N ha^{-1} of the N applied to the cover crop was still present. The cover crop planted in 2002 used only 4% of ^{15}N fertilizer applied to the 2001 cover crop (1.3 kg N). Similarly, the following cotton crop used 6% (1.9 kg N) of fertilizer applied to the cover crop in 2001, in line with the second year of the 2000 cover crop fertilization. This indicates that much of the fertilizer N had become incorporated in the SOM, since 29.2 kg N ha^{-1} or 86% of fertilizer N was still in the soil–plant system 2 yr after application, with only a small percentage assimilated by plants (6%).

Table 3. Fertilizer ^{15}N uptake of plants and soil, total N uptake in plant–soil system, N use efficiency in plants, and soil C/N ratios of microplots established with N fertilization of rye cover crop. Microplots are within strip plots of a high-residue cover crop conservation tillage system located in the Tennessee Valley of Alabama. Microplots were fertilized at a rate of 34 kg N ha^{-1} on cover crops and 90 kg N ha^{-1} on cotton.

Year	Crop	Fertilizer ^{15}N Plant	Soil†	Soil–plant system	Plant N efficiency‡	Soil C/N ratio†
		kg N ha^{-1}			%	
		2000 growing season ^{15}N rye application				
2000	rye	18.0	–	–	53	–
	cotton	10.2	21.2	31.4	30	10:1§
2001	rye	0.9	–	–	3	–
	cotton	2.8	26.6	29.4	8	13:1§
2002	rye	0.9§	–	–	3	–
	cotton	0.9§	15.5	16.4	1	10:1§
		2001 growing season ^{15}N rye application				
2001	rye	12.6	–	–	37	–
	cotton	5.2	27.2	32.4	15	13:1§
2002	rye	1.3	–	–	4	–
	cotton	1.9	27.3	29.2	6	10:1§
		2002 growing season ^{15}N rye application				
2002	rye	25.6	–	–	75	–
	cotton	2.9§	26.8	29.7	3	10:1§

† Samples taken after cotton harvest each year only.

‡ Efficiency of uptake of original ^{15}N fertilizer applications (total N plant/applied amount × 100).

§ Not a significant difference from 0-N control.

In 2001 (Tables 1 and 4), cotton's FUE was 51% (45.7 kg N) of N applied at the beginning of the 2001 cotton growing season. These results are consistent with findings from other research in cotton conservation tillage systems (Torbert and Reeves, 1994). Inconsequential recovery of N from the 2001 cotton treatment was observed for the cover crop and cotton in 2002; however, 31.4 kg N ha^{-1} (35%) of ^{15}N fertilizer applied to cotton on 4 May 2001 was found in soil sampled after cotton harvest in 2002. It is unlikely that ^{15}N inorganic N remained in the soil at the depth sampled (46 cm) for 18 mo in this humid climate, suggesting immobilization of fertilizer N within the microbial biomass and concurrent mobilization of untraceable N given a soil C/N ratio of 10:1; however, the exact N form could not be determined from the measurements taken.

Enriched ^{15}N fertilizer applications in 2002 to the cover crop (Tables 1 and 3) (established with 2002 cover crop fertilization) had results similar to previous years; however, the 2002 cover crop showed the highest N FUE, with 75% (25.6 kg N) of applied N being utilized. Due to the low soil C/N ratio found after the 2002 cotton sampling (10:1), we speculate that much of this ^{15}N was immobilized in organic forms while nonfertilizer N was mineralized, as no significant amounts of N from the 2002 cover crop fertilization was used by the 2002 cotton crop and 26.8 kg N ha^{-1} (79%) was still in the soil from the ^{15}N fertilization at the final sampling after cotton harvest.

Fertilization of cotton in the third year (Tables 1 and 4) (established with fertilization of the 2002 cotton crop) showed a 45% (40.4 kg N) FUE. Upon final sampling, 72.8 kg N ha^{-1} (81%) of traceable cotton fertilizer N was still in the soil–plant system, with a soil C/N ratio of 10:1.

Fertilizer use efficiency was also calculated using the difference method (Table 5). Higher FUE was found with the difference method than the direct ^{15}N fertilizer measurements and suggested that nonfertilizer N was assimilated by both cover crop and cotton plants or that isotope substitution occurred. Difference FUE suggested that 81, –2, and 22% more fertilizer N (difference FUE % – ^{15}N FUE %) was utilized by the cover crops for 2000, 2001, and 2002, respectively (Table 5). Cotton

Table 4. Fertilizer ^{15}N uptake of plants and soil, total N uptake in plant–soil system, N use efficiency in plants, and soil C/N ratios of microplots established with N fertilization of cotton crop. Microplots are within strip plots of a high-residue cover crop conservation tillage system located in the Tennessee Valley of Alabama. Microplots were fertilized at a rate of 34 kg N ha^{-1} on cover crops and 90 kg N ha^{-1} on cotton.

Year†	Crop	Fertilizer ^{15}N Plant	Soil‡	Soil–plant system	Plant N efficiency§	Soil C/N ratio‡
		kg N ha^{-1}			%	
		2001 growing season ^{15}N cotton application				
2001	cotton	45.7	42.1	87.8	51	13:1¶
2002	rye	2.5¶	–	–	7	–
	cotton	2.5¶	31.4	33.9	3	10:1¶
		2002 growing season ^{15}N cotton application				
2002	cotton	40.4	32.4	72.8	45	10:1¶

† 2000 cotton growing season application missing due to initial misapplication of fertilizer.

‡ Samples taken after cotton harvest each year only.

§ Efficiency of uptake of original ^{15}N fertilizer applications (total N plant/applied amount × 100).

¶ Not a significant difference from 0-N control.

Table 5. Fertilizer N uptake and N efficiency in a high-residue cover crop conservation tillage system located in the Tennessee Valley of Alabama for plots fertilized with 34 kg N ha^{-1} on cover crops and 90 kg N ha^{-1} on cotton.

Year	Cover crop		Cotton	
	N uptake	N efficiency†	N uptake	N efficiency†
	kg N ha^{-1}	%	kg N ha^{-1}	%
2000	103.1	134	89.7	50
2001	29.6	35	137.0	86
2002	71.0	97	127.7	67

† N efficiency = (N uptake – 0-N control)/N rate applied.

had similar results, as 35 and 22% more fertilizer N was assimilated in 2001 and 2002, respectively.

Cotton Leaf Nitrogen Levels at First Flower

Leaf N at first flower had a linear relationship with cotton lint yield (lint yield = 291.83 + 20.94x, R^2 = 0.58); therefore, higher N status provided higher lint yields. Mills and Jones (1996) suggested a leaf N concentration at first bloom between 35.0 to 45.0 g N kg^{-1}, while Wood et al. (1992) found maximum economic cotton yield with 54 g tissue N kg^{-1} at first flower, which no treatment in our study achieved. Due to yearly variability of leaf N concentrations in our study, we assumed the lowest value proposed by Mills and Jones (1996) as the sufficiency minimum (35.0 g N kg^{-1}).

In 2000, if 0 N was applied to the cover crop, 45 kg N ha^{-1} was needed by the cotton crop for the highest concentrations of leaf N (33.6 g N kg^{-1}) (Table 6). With 34 kg N ha^{-1}applied to the rye cover crop, 135 kg N ha^{-1} applied to cotton was required to maximize leaf N concentration. Similarly, cotton following a cover crop fertilized with 67 kg N ha^{-1} had higher leaf N when 135 kg N ha^{-1} was applied to cotton compared with 0 and 45 kg N ha^{-1}. At all three cover crop N rates, application of 135 kg N ha^{-1} to cotton was needed to bring leaf N levels into the sufficiency range suggested by Mills and Jones (1996) (35.0–45.0 g N kg^{-1}).

Table 6. Interaction of cover crop N rate (0, 34, 67 kg N ha^{-1}× cotton N rate (0, 45, 90, and 135 kg N ha^{-1}) on cotton leaf N at first flower for a high-residue conservation tillage system located in the Tennessee Valley of Alabama in 2000, 2001, and 2002.

Year	Cover crop N rate	Cotton leaf N			
		0 kg N	45 kg N	90 kg N	135 kg N
	kg N ha^{-1}	g N kg^{-1}			
2000†	0	29.6‡	33.6‡	33.8‡	35.2
	34	30.5‡	28.9‡	34.5‡	37.3
	67	29.4‡	32.9‡	34.8‡	35.8
2001§	0	27.4‡	28.1‡	29.3‡	30.7‡
	34	29.6‡	28.4‡	31.3‡	32.8‡
	67	28.3‡	29.4‡	30.6‡	32.7‡
2002¶	0	37.4	41.6	44.1	44.8
	34	40.2	41.0	45.3	45.0
	67	42.3	42.5	45.0	44.6

† 2000 LSD(0.10) for cover crop rate at same cotton rate (down) within year = 2.7 g N kg^{-1}; for cotton rate at same cover crop rate (across) within year = 2.6 g N kg^{-1}.

‡ Insufficient leaf N at first flower (35.0 g N kg^{-1}).

§ Not a significant difference so LSD is not shown. Means are for informational purposes only.

¶ 2002 LSD(0.10) for cover crop rate at same cotton rate (down) within year = 2.0 g N kg^{-1}; for cotton rate at same cover crop rate (across) within year = 1.5 g N kg^{-1}.

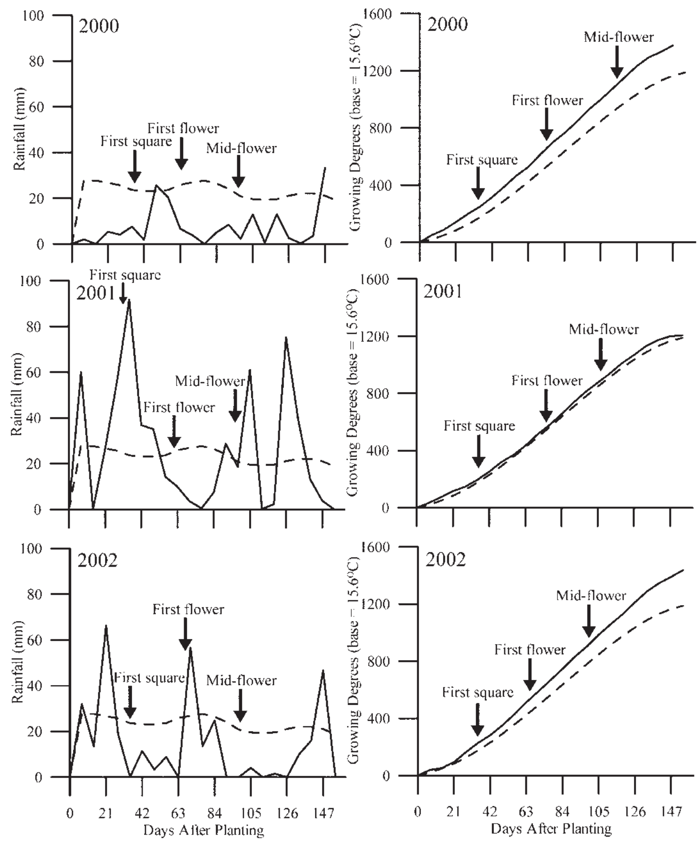

Fig. 2. Precipitation and growing degree heat unit (base = 15.6°C) patterns from planting to harvest of cotton crop in the Tennessee Valley of Alabama in 2000, 2001, and 2002: yearly pattern (solid line) and 30-yr average (broken line).

In 2001, cotton leaf N was not statistically affected by rye or cotton N applications (Table 6). No N treatment combination provided sufficient cotton leaf N status at first flower (35.0 g N kg^{-1}) (Mills and Jones, 1996).

In 2002, levels of leaf N (Table 6) were above the Mills and Jones (1996) sufficiency level for all treatments but still lower than concentrations suggested by Wood et al. (1992). Stressed plants from dry weather (Fig. 2) probably lowered cotton plant residue in 2002, which contributed to higher N levels through a concentration effect. Only 90 kg N ha^{-1} was needed on cotton in 2002 to reach peak leaf N concentrations for all cover crop treatments (44.1, 45.3, and 45.0 g N kg^{-1} for 0, 34, and 67 kg N ha^{-1}, respectively). With low rates of N loss from cover crop treatments, illustrated with 75% N use efficiency from ^{15}N applied to the cover crop (Table 3), it is intuitive that N mineralized in rye residue would be available to cotton in 2002. Nitrogen mineralization from cover crop residue would explain high cotton leaf N levels when 0 N was applied to cotton (37.4, 40.2, and 42.3 g N kg^{-1} for 0, 34, and 67 kg N ha^{-1}, respectively). An insignificant amount of ^{15}N fertilizer applied to the cover crop in 2002 was used by the 2002 cotton crop, however, even though soil C/N ratios were low after cotton harvest (10:1).

Table 7. Cotton N rate main effect (2000) and interaction of cover crop N rate × cotton N rate (2001 and 2002) on cotton lint yield for a high-residue conservation tillage system located in the Tennessee Valley of Alabama.

Cover crop N rate	Equation†	$P > F$	R^2	Economic optimum cotton N rate‡	Asymptotic maximum yield cotton N rate§	Asymptotic maximum cotton yield¶
kg N ha^{-1}				kg N ha^{-1}		kg lint ha^{-1}
				2000		
Avg.#	$894.9 + 5.36N - 0.032N^2$	0.0149	0.88	73	84	1119
				2001		
0	$640.4 + 7.32N - 0.035N^2$	0.0002	0.99	95	105	1023
34	$693.5 + 2.33N$	0.0006	0.91	135	135	1008
67	$809.0 + 5.73N - 0.036N^2$	0.0021	0.85	70	80	1037
				2002		
0	$898.5 + 7.52N - 0.035N^2$	0.0010	0.91	97	107	1302
34	$1042.1 + 5.80N - 0.038N^2$	0.0317	0.82	67	76	1263
67	$1076.5 + 4.39N - 0.026N^2$	0.1204	0.69	71	84	1262

† Highest order significant model presented.

‡ Derived by setting model equal to N/lint price ratio (US$0.82/US$1.17 = 0.70). Highest N rate used for linear models.

§ Asymptotic peak for quadratic models and highest N rate applied for linear models.

¶ Found using model and maximum yield cotton N rate presented.

Averaged across cover crop N rates; mean cover crop N rate = 34 kg N ha^{-1}.

Lint Yield

Neither cover crop N application alone or in interaction with cotton N application affected cotton lint yield in 2000; however, a quadratic response was observed with the cotton N rate main effect (Table 7, Fig. 3). Regardless of cover crop N rate (34 kg N ha^{-1} on average), cotton N applications of 84 kg N ha^{-1} provided maximum lint yield (1119 kg lint ha^{-1}), while 73 kg N ha^{-1} was projected as the economic optimum N rate.

There was a cover crop N rate × cotton N rate interaction in 2001 (Table 7, Fig. 3). Highest yields were obtained with either 0-N on the cover crop and 105 kg N ha^{-1} on cotton (1023 kg lint ha^{-1}), 34 kg N ha^{-1} on the cover crop and 135 kg N ha^{-1} on cotton (1008 kg lint ha^{-1}), or 67 kg N ha^{-1} on the cover crop and 80 kg N ha^{-1} on cotton (1037 kg lint ha^{-1}). Lower cover crop C/N ratios (21:1) from higher cover crop N rates (67 kg N ha^{-1}) (Table 2) allowed N to mineralize during the growing season and provide N to cotton. A cover crop N rate of 67 kg N ha^{-1} and cotton N rate of 80 kg N ha^{-1} provided maximum yields (Table 7, Fig. 3); however, the rising costs of N fertilizer may prohibit such an application. Optimum economic yields were estimated at N cotton application rates of 70 kg N ha^{-1} if 67 kg N ha^{-1} was applied to rye cover crops. The current production practice of 0-N to cover crops required a cotton N rate 57% higher (38 kg N ha^{-1}) than the median recommended N rate (67 kg N ha^{-1}) and provided sufficient yields (1023 kg lint ha^{-1}) (Adams and Mitchell, 2000).

In 2002, there was again a cover crop N rate × cotton N rate interaction effect on lint yield (Table 7, Fig. 3). Maximum yield was achieved with unfertilized rye cover crop plots and 107 kg N ha^{-1} applied to cotton, which was 60% more N (40 kg N ha^{-1}) than the currently recommended median N rate. Nitrogen was mineralized from the rye cover crop fertilization and made available to the cotton crop; however, excessive cotton vegetative growth and leaf N concentrations may have inhibited higher yields. Overall, 2002 data suggest that it may be practical for farmers to fertilize their cover crop and reap benefits. Similar total (cover crop N rate + cotton N rate) N rate applications were necessary for maximum cotton yields (0 kg cover crop N ha^{-1} + 107 kg cotton N ha^{-1} vs. 34 kg cover crop N ha^{-1} + 76 kg cotton N ha^{-1}) (Table 7, Fig. 3), but more cover crop biomass (1793 kg ha^{-1}) was produced for soil protection and SOM accumulation when the cover crop was fertilized (Table 2).

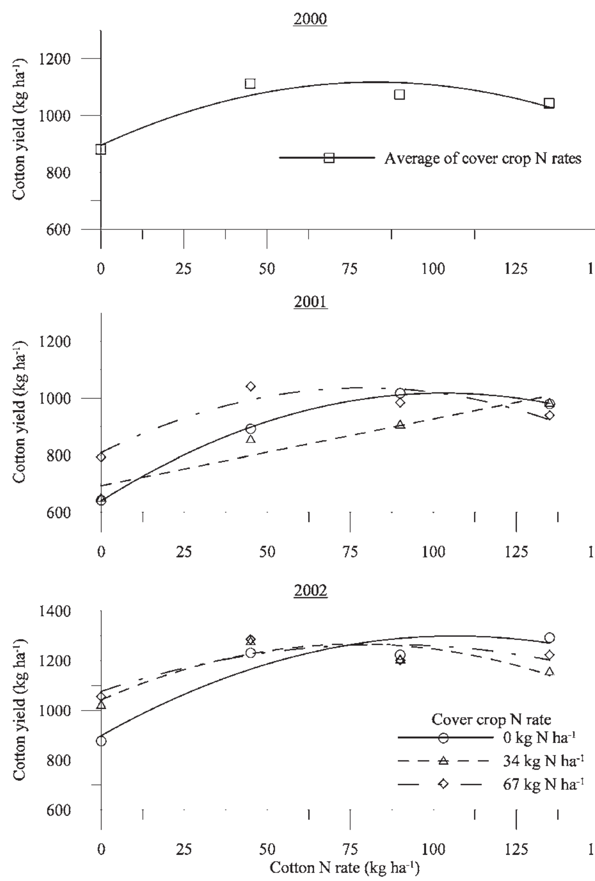

Fig. 3. Cotton N rate main effect (2000) and cover crop N rate × cotton N rate interaction (2001 and 2002) on cotton lint yield for a high-residue conservation tillage system located in the Tennessee Valley of Alabama. See Table 7 for equation and fit statistics.

Table 8. Significant cotton lint quality data for cotton N rate main effect for a high-residue conservation tillage system located in the Tennessee Valley of Alabama in 2000, 2001, and 2002, averaged across cover crop N rates.

Cotton N rate	2000			Fiber length	
	Ginning percentage	Micronaire	Length uniformity ratio	2001	2002
kg N ha^{-1}	%		%	—— mm ——	
0	41.9	4.13	84.5	27.8	27.6
45	40.8	4.36	83.5	27.7	27.2
90	40.0	4.29	83.8	27.9	27.4
135	40.0	4.25	83.5	28.2	27.2
LSD(0.10)	1.0	0.10	0.7	0.3	0.3

Overall, maximum economic cotton N rate recommendations were generally 10% lower than maximum yield calculations in all years (Table 7); however, maximum economic N rate calculations do not include any analysis in regard to cover crop N rate. It is difficult to assign monetary values to the decreased soil erosion and improved soil quality that result from significant contributions of soil organic matter. Farm payments for C sequestration credits and reducing erosion place monetary values on cover crop and C storage potential and may pay for extra fertilizer costs, as discussed in detail by Causarano et al. (2006).

Cotton Quality

Overall, cover crop fertilization had inconsequential impacts on cotton lint qualities. Cover crop treatments slightly affected fiber length, as 67 kg N ha^{-1} applications produced longer fiber (28.2 mm) in 2001 than 0 and 34 kg N ha^{-1} (27.8 and 27.7 mm), averaged across cotton N rates. A similar occurrence with cotton N rate in 2001 indicated that 135 kg N ha^{-1} gave a slight length advantage over other treatments when averaged across cover crop N rates (Table 8). These results agree with Bauer and Roof (2004), who indicated higher fiber lengths when cotton was fertilized. Lower cotton N rates were needed to achieve maximum length in their study, however, possibly due to lower cover crop biomass production.

Averaged across cover crop N rates, ginning percentage decreased as N rates applied to cotton increased in 2000 (Table 8). Elbehar (1991) found similar results and attributed lower ginning turnout percentage to higher seed weights due to excess N. Nitrogen has a higher impact on seed weights than on lint weight. Ginning percentage was not significant in 2001 or 2002 but had mean values of 38.5 and 38.1%, respectively.

Micronaire was highest for the 45 and 90 kg N ha^{-1} cotton treatments in 2000 (Table 8), averaged across cover crop N rates, similar to the findings of Bauer and Roof (2004). Sufficient N supplies are needed to obtain base range micronaire readings (3.50–4.90; USDA, 1999). Micronaire was not affected by N fertility in 2001 and 2002, with mean values of 4.01 and 3.05, respectively.

A higher length uniformity ratio was obtained with the 0-N treatment than cotton fertilizer treatments averaged across cover crop N rates in 2000 (Table 8). Length uniformity is the ratio between the mean length and the upper half mean length of the fibers (USDA, 1999). A difference of maturity in bolls is probably a cause of higher N rates having more variable cotton length; however, all treatments were in the high range (83–85%) according to the USDA (1999). Lint strength was not significantly impacted by N fertilization and had a mean value of 259.3 kN m kg^{-1}.

CONCLUSIONS

Nitrogen application combinations for maximum lint yield was an average of 34 kg cover crop N and 84 kg cotton N ha^{-1}, 67 kg cover crop N and 80 kg cotton N ha^{-1}, and 0 kg cover crop N and 107 kg cotton N ha^{-1} for 2000, 2001, and 2002, respectively. Economic optimum cotton N rates were generally 10% lower than maximum yield N rates; however, the highest cover crop biomass production for soil erosion protection, soil C aggradation, and soil quality improvement resulted from 67 kg N ha^{-1} applied to the cover crop, while the cotton N rate was inconsequential regarding cover crop biomass production. If the cover crop was fertilized, at least 67 kg N ha^{-1} was needed for economic optimal lint yield and 76 kg N ha^{-1} resulted in maximum cotton yield. If no N was applied to the cover crop, 57 to 60% (38–40 kg N ha^{-1}) more N was needed than the standard conventional tillage application recommendation (67 kg N ha^{-1}) for the highest cotton yields. We speculate that N requirements may be reduced with time in high-residue systems as soil C and N pools reach new equilibria.

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