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AGRONOMY AND SOILS

Potassium and Magnesium Nutrition of Cotton Fertilized with Broiler Litter

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ABSTRACT

Poultry litter is an effective N fertilizer for cotton. Litter contains substantial amounts of K and Mg also, but whether the K and Mg needs of cotton can be met by the commonly recommended litter rate has not been documented. The objectives of this research were to determine if cotton receives sufficient K from the application of the commonly recommended litter rate of 4.5 Mg ha^{-1} and if Mg derived from the same litter rate improves cotton Mg nutrition. The research was conducted from 2002 to 2004 in Mississippi at Coffeeville and Cruger, which had contrasting soil K and Mg levels. The soil at Coffeeville had approximately five times less extractable K and approximately 22 times less extractable Mg than the soil at Cruger. Cotton at each location was fertilized with 2.2, 4.5, or 6.7 Mg ha^{-1} broiler litter in an incomplete factorial combination with 0, 34, or 67 kg ha^{-1} N as urea-ammonium nitrate solution (UAN). The results showed cotton received sufficient K from 4.5 Mg ha^{-1} litter, a rate previously found to be insufficient in meeting the N requirement of cotton. Unlike K, Mg concentration in the plant did not respond to increased applied litter rate but showed a strong response to supplemental UAN-N rate, which suggests the external N supply might be more important to cotton Mg nutrition than the external Mg supply. The results showed that K nutrition of cotton depended on the rate of applied litter, whereas Mg nutrition is dependent on whether the cotton received sufficient N fertilization.

Potassium is one of the two most abundant mineral nutrients in cotton (*Gossypium hirsutum* L.), with N being the other. In some situations, K might be more abundant than N in cotton plants (Tewolde et al., 2005). Potassium is an important major nutrient in cotton production because it affects yield and fiber quality substantially (Bauer et al., 1998; Cassman et al., 1990; Girma et al., 2007; Mullins et al., 1997). In recent years, K has been recognized as a key nutrient in the major cotton producing regions of the US as indicated by intensifying K fertilization research and increasing K fertilization rates during the last 20 to 25 yr (Snyder et al., 2005).

Poultry litter is an effective cotton fertilizer and, in some soils, it might be a better fertilizer than conventional inorganic fertilizers (Endale et al., 2002; Mitchell and Tu, 2005; Tewolde et al., 2007a, 2008). Litter is applied to row crops including cotton, at rates intended to meet either the N or P needs of the crop. Usually it is also expected to supply K, but often K is not the target nutrient. Ideally, the K need of the target crop can be met by the amount of litter usually applied to meet the N or P needs of cotton.

Magnesium is not as abundant as K in the cotton plant but is another essential nutrient for cotton production. Magnesium is added to cotton soils in rare situations, such as in some sandy or acidic soils. Litter contains substantial amounts of Mg. Cotton can extract litter-derived Mg as efficiently as K (Tewolde et al., 2005).

No documented research has evaluated whether the K requirement of cotton can be met by fertilizing with poultry litter applied to meet either the N or P need of cotton, or whether litter-derived Mg benefits cotton production. This research investigated the K and Mg nutrition of cotton as part of a larger research program that studied the feasibility of using broiler litter as a primary cotton fertilizer in the mid-south US. The objectives were to determine if cotton receives sufficient K fertilization from the application of the commonly recommended litter rate of 4.5 Mg ha^{-1} for optimum lint yield, and if Mg derived from the same amount of litter improves cotton Mg nutrition in two Mississippi soils with contrasting levels of extractable K and Mg.

MATERIALS AND METHODS

The research was conducted on two commercial farms from 2002 to 2004 under no-till at Coffee-

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ville, MS (33.97° N, 89.68° W, 71.2 m altitude) and under conventional-till at Cruger, MS (33.30° N, 90.23° W, 32.9 m altitude). The soil at Coffeeville was an Ariel silt loam (coarse-silty, mixed, thermic Fluventic Dystrochrept) and the soil at Cruger was a Dubbs silt loam (fine-silty, mixed, active, thermic Typic Hapludalf). Cotton was grown on the same soil continuously for 4 yr at Coffeeville and for more than 25 yr at Cruger before initiating this research.

Treatments and Design. Cotton at each location was fertilized with fresh broiler-litter rates of 2.2, 4.5, and 6.7 Mg ha^{-1} in an incomplete-factorial combination with 0, 34, or 67 kg ha^{-1} N side-dressed as UAN solution. Eight of the nine possible combinations of litter (L) and UAN nitrogen (N) included: $L_{2.2}N_0$, $L_{2.2}N_{34}$, $L_{2.2}N_{67}$, $L_{4.5}N_0$, $L_{4.5}N_{34}$, $L_{4.5}N_{67}$, $L_{6.7}N_0$, and $L_{6.7}N_{34}$, where the subscripts represent the litter (Mg ha^{-1}) or N (kg ha^{-1}) fertilization rates. An unfertilized control (L_0N_0) and a farm standard fertilization treatment (Std) were also included for a total of 10 treatments.

The 10 treatment combinations within each location were tested in a randomized complete block design with three or four replications. The plots consisted of eight 73-m-long rows spaced 0.97 m apart at Coffeeville and four 119-m-long rows spaced 1.02 m apart at Cruger. Each treatment was applied to the same plot in all 3 yr. Each year, UAN (32% N) was applied between first square and flower stage as a side-dress using a commercial liquid fertilizer applicator equipped with coulters that opened slits about 0.15 to 0.20 m away from the row center into which the UAN solution was injected to a depth of approximately 0.10 m. Inorganic N, P, and K fertilizers were applied to the Std at the same rate as adjacent fields as practiced by the respective farm. The Std treatment at Coffeeville received 101 kg N ha^{-1} in 2002 and 118 kg N ha^{-1} in 2003 and 2004 as UAN. Under conventional-till at Cruger, the Std treatment received 135 kg N ha^{-1} yr^{-1} as UAN. Phosphorus was applied as triple superphosphate (0–46–0) to the Std treatment at 29, 20, and 0 kg P ha^{-1} at Coffeeville and 0, 20, and 0 kg P ha^{-1} at Cruger in 2002, 2003, and 2004, respectively. Potassium was applied to the Std treatment as KCl (0–0–60) at 56, 75, and 112 kg K ha^{-1} at Coffeeville and 140, 98, and 93 kg K ha^{-1} at Cruger in 2002, 2003, and 2004, respectively. All P and K fertilizers were applied to the Std as a broadcast before planting.

Litter was applied on 29 Apr. 2002, 27 May 2003, and 7 May 2004 at Coffeeville and on 16 Apr. 2002, 15 Apr. 2003, and 9 Apr. 2004 at Cruger. Each year, the litter was broadcast-applied with a commercial fertilizer spreader equipped with ground-speed sensing radar, an electronic scale, and a rate-control computer system (Barrons & Brothers, Inc., Gainsville, GA). Litter was soil-incorporated on the day of application under conventional-till at Cruger but was not incorporated under no-till at Coffeeville. Cotton was planted on 21 May 2002, 2 May 2003, and 28 Apr. 2004 at Coffeeville and on 19 Apr. 2002, 16 Apr. 2003, and 19 Apr. 2004 at Cruger. Additional details on soil and litter properties, crop management, and weather were reported earlier (Tewolde et al., 2007a).

Soil and Plant Sampling and Analysis. Background soil samples (0–0.15 m) were taken before any fertilization on 23 Apr. 2002 (Coffeeville) and 16 Apr. 2002 (Cruger) and at the conclusion of the research on 10 Nov. 2004 (Coffeeville) and 6 Oct. 2004 (Cruger). The samples were air-dried and ground to pass through a 2-mm sieve. Approximately 2 g of the air-dried and ground soil sample were extracted with 10 mL Mehlich 3 extractant and analyzed for K and Mg with an inductively coupled, dual axial, Argon plasma spectrophotometer (ICP, Thermo Jarrell-Ash Model 1000, Franklin, MA).

Above-ground whole plant samples were harvested from 0.5- to 0.6-m^2 center rows of each plot at flowering (31 Jul. 2002 at Coffeeville; 25 Jul. 2002 and 23 Jul. 2003 at Cruger) and at the end of the season (10 Sept. 2002, 16 Sept. 2003, and 13 Sept. 2004 at Coffeeville; 27 Aug. 2002, 29 Aug. 2003, and 31 Aug. 2004 at Cruger) to measure K and Mg concentration and uptake. Approximately 25 petioles of the youngest fully expanded mainstem leaves were collected from 25 randomly selected plants in each plot at the same time as the whole plant samples to measure petiole K and Mg concentration.

Whole plants from both locations were cut at soil level and separated by hand into leaves (leaf blade + petioles), stems (branches + main stem), and reproductive parts (squares + flowers + bolls). Reproductive parts were further separated into burs, seed, and lint when bolls were mature enough to make the separation feasible. The lint was separated from seed using a 10-saw gin. The petiole samples and all other plant parts from the whole plant samples were dried in a forced-air oven at 80 °C to constant weight, weighed, and ground to pass through a 1-mm sieve. Seed samples were delinted with H_2SO_4 before grinding because linters on seed made homogenization extremely difficult.

Approximately 0.5 g ground petiole samples were extracted with deionized water and K and Mg concentration determined by ICP (Donohue and Aho, 1992). Concentrations of K and Mg in samples from the whole plant parts were also measured with the ICP after ashing 0.2 g of the dried and ground sample in a muffle furnace at 500 °C for 4 h. The ash was digested with 1.0 mL 6 *M* HCl for 1 h and 40 mL of a double-acid solution containing 0.0125 *M* H_2SO_4 and 0.05 *M* HCl for an additional 1 h. The digested solution was then filtered using a 2V Whatman filter paper (Whatman, Maidstone, UK) and analyzed for total K and Mg concentration with the ICP. Concentrations of K and Mg in the litter (Table 1) were determined by the same method used for the plant tissues.

Table 1. Moisture content and concentration of N, P, K, and Mg of broiler litter applied to cotton at Coffeeville (no-till) and Cruger (conventional-till), MS from 2002 to 2004

Location	Year	Moisture	N	P	K	Mg
			$g\ kg^{-1}$			
Coffeeville	2002	229	33.5	18.9	30.7	6.8
	2003	280	28.1	12.7	29.2	5.8
	2004	265	31.3	12.8	29.1	5.8
	Avg.	258	31.0	14.8	29.7	6.1
Cruger	2002	342	23.6	16.9	24.8	4.6
	2003	391	26.3	10.3	25.0	5.1
	2004	261	26.0	11.8	28.9	5.7
	Avg.	331	25.3	13.0	26.2	5.1

Accumulation of K and Mg in each plant part was calculated by multiplying K and Mg concentration in a plant part by its dry weight. Total K or total Mg uptake by above-ground plant parts was determined as the sum of the respective element accumulated in leaves, stems, and reproductive parts. Concentration of K and Mg was not analyzed in all lint samples because the K and Mg content of lint was expected to be low. Total K and Mg accumulation in lint was therefore determined by multiplying the lint dry weight of each sample by an average lint K and Mg concentration measured on all lint samples from one year-location.

Statistical Analysis. Litter and supplemental UAN-N effects on K and Mg concentration in each plant part and the amount of K and Mg accumulated in each plant part were tested by subjecting the data to analysis of variance using the PROC MIXED procedure of Statistical Analysis Systems (Littell et al., 2002). Preliminary ANOVA was performed for a randomized complete block design with a factorial treatment structure for litter and UAN-N factors. Additional analysis was performed using a trend to describe the litter and UAN-N treatment structure as a response surface model, where the full model had three slope parameters that included litter linear (L_L), UAN-N linear (N_L), and their interactions ($L_L \times N_L$). When the $L_L \times N_L$ interaction term in the full model was not significant, it was deleted from the model leaving only the linear effect (L_L and N_L) terms. Regression analysis was used to test the relationship between selected measurements. All differences mentioned in the discussion are significant at $P \leq 0.05$ unless stated otherwise.

RESULTS AND DISCUSSION

Potassium

Extractable Soil Potassium. The soil at Coffeeville had 49 mg kg^{-1} Mehlich 3 extractable K (M3K) immediately before initiating the experiment in 2002. The soil at Cruger had 233 mg kg^{-1} M3K, nearly 4.8 times more than that of the Coffeeville soil. Based on University of Arkansas recommendations, which uses Mehlich 3 extraction (Espinoza, personal commun., 2003), cotton should have been fertilized with 105 kg K ha^{-1} at Coffeeville and 0 kg K ha^{-1} at Cruger for optimum lint yield. Instead, the growers at both Coffeeville and Cruger, who use independent soil analysis labs, received recommendations to apply 56 kg K ha^{-1} at Coffeeville and 140 kg K ha^{-1} at Cruger in the first year in 2002. The Std treatment in our research received the same K recommendations as used on the respective farms to reflect common farm practices.

At the conclusion of the research in 2004, soil K accumulated proportional to applied litter rate. Litter had a significant linear effect on M3K concentration in the top 0.15 m soil at both locations (Table 2). At Coffeeville, when no supplemental UAN-N was applied, M3K increased from 40 mg kg^{-1} for the L_0N_0 treatment to 85 mg kg^{-1} for the $L_{6.7}N_0$ treatment. Similar increasing trends were found at 34 or 67 kg ha^{-1} supplemental UAN-N levels. The response of soil M3K at Cruger was similar to the response at Coffeeville regardless of the level of supplemental UAN-N (Table 2). The Std treatment at both locations had less soil M3K than the highest litter treatment of 6.7 Mg ha^{-1} at both locations. The results suggest applying 4.5 Mg ha^{-1} or more litter might lead to soil K accumulation.

Table 2. End-of-season Mehlich 3 extractable K and Mg concentration in soils (0– 0.15 m depth) that received broiler litter with or without supplemental N as UAN from 2002 to 2004 at Coffeeville (no-till) and Cruger (conventional-till), MS

Treatment[z]	Coffeeville, 10 Nov. 2004		Cruger, 6 Oct. 2004	
	K ($mg\ kg^{-1}$)	Mg ($mg\ kg^{-1}$)	K ($mg\ kg^{-1}$)	Mg ($mg\ kg^{-1}$)
L_0N_0	40	40	218	397
$L_{2.2}N_0$	48	46	224	370
$L_{4.5}N_0$	72	62	264	388
$L_{6.7}N_0$	85	64	258	381
$L_{2.2}N_{34}$[y]	49	50	234	372
$L_{4.5}N_{34}$	69	54	244	387
$L_{6.7}N_{34}$	95	70	254	398
$L_{2.2}N_{67}$[y]	41	57	223	362
$L_{4.5}N_{67}$	89	72	250	411
Std	66	41	235	382
ANOVA		*P* > *F*		
L_L[x]	0.009	0.006	0.029	0.373
N_L	0.014	0.048	0.993	0.801

[z] Treatment combinations shown as L (litter) and N (UAN-N) with the subscripts representing rates of applied litter ($Mg\ ha^{-1}$) or N ($kg\ ha^{-1}$). Std = farm standard fertilization.

[y] Supplemental UAN-N rates in 2004 at Cruger were 67 and 135 $kg\ ha^{-1}$ instead of the 34 and 67 $kg\ ha^{-1}$ applied in 2002 and 2003.

[x] L_L=Litter linear effect; N_L= UAN-N linear effect.

Response of K Concentration in Plant Parts to Applied Litter. Potassium concentration in plant parts responded to applied litter at both Coffeeville and Cruger. Concentration of K in petioles, bulk leaves, stems, and reproductive parts increased linearly with increased litter application rate at nearly all location-years (Table 3). This response suggested that cotton received K in proportion to the rate of applied litter and that the litter K was readily available for uptake by cotton. A prior test with container-grown cotton showed that cotton absorbs litter-derived K with greater efficiency than the other litter-derived macronutrients including N and P (Tewolde et al., 2005).

The response of K concentration in plant parts to applied litter at Coffeeville was not surprising because the soil at this location had low extractable soil K. The significant K concentration response to applied litter at Cruger was unexpected but, as one earlier report suggested (Pettiet, 1988), this might be related to the high soil test Mg. The soil at Cruger had Mehlich 3 extractable Mg (M3Mg) of 465 mg kg^{-1} compared to 20.8 mg kg^{-1} at Coffeeville. Pettiet (1988) reported that high exchangeable Mg concentration in Mississippi Delta soils might be primarily responsible for cotton yield response to K fertilization, although these soils had higher than normal soil test K. The Cruger site is located in the Mississippi Delta and the soil is characteristic of the alluvial floodplain soils in the region, whereas the Coffeeville site is outside the Mississippi Delta region. Cotton is also known to respond to K fertilization in other soils with high soil test K (Essington et al., 2002).

Sufficiency of Litter-Derived K. Cotton fertilized with the $L_{4.5}N_{67}$ or $L_{6.7}N_{34}$ treatments consistently produced as much or greater lint yield than the Std treatment at all location-years (Tewolde et al., 2007a). Fiber quality of these two treatments also was as good as or better than that of the Std treatment. The equal or better yield performance of the $L_{4.5}N_{67}$ or $L_{6.7}N_{34}$ treatments relative to the Std suggests cotton fertilized with ≥ 4.5 Mg ha^{-1} litter received sufficient K and other essential nutrients assuming the Std treatment received sufficient fertilization of K and other nutrients.

Comparison of leaf and petiole K concentrations for litter versus the Std treatment showed that cotton received sufficient K for optimum lint yield when fertilized with litter as low as 4.5 Mg ha^{-1}. At Coffeeville, cotton fertilized with the Std treatment, which received 56 kg K ha^{-1} as KCl, had 20 g kg^{-1} bulk leaf K concentration and 37 g kg^{-1} petiole K concentration (Table 3). Relative to the Std, the $L_{4.5}N_{67}$ treatment, which supplied 143 kg ha^{-1} litter-derived K (Table 4) at this location, increased bulk leaf K concentration by 24% and petiole K concentration by 20%. The $L_{6.7}N_{34}$ treatment, which supplied 206 kg ha^{-1} litter-derived K, increased bulk leaf K and petiole K concentrations by the same or greater percentages (37 and 20%), respectively. At Cruger, cotton fertilized with the Std treatment, which received an average across the 2 yr of 119 kg K ha^{-1} as KCl (Table 4) had 26 g kg^{-1} bulk leaf K concentration and 59 g kg^{-1} petiole K (averaged across the 2 yr) (Table 3). Unlike Coffeeville, the two treatments at Cruger ($L_{4.5}N_{67}$ and $L_{6.7}N_{34}$), which supplied an average across years of 108 and 169 kg ha^{-1} litter-derived K, respectively, did not increase bulk leaf or petiole K concentration above the Std treatment. The lack of increase of K concentration of the $L_{4.5}N_{67}$ and $L_{6.7}N_{34}$ treatments relative to the Std at Cruger may be because the Std at Cruger received inorganic K (110 kg K ha^{-1}) comparable to at least that of the $L_{4.5}N_{67}$ treatment. The Std treatment at this location, unlike at Coffeeville, yielded as much lint as the $L_{4.5}N_{67}$ and $L_{6.7}N_{34}$ treatments (Tewolde et al., 2007a) suggesting that this treatment received sufficient K fertilization from the inorganic fertilizers. At Coffeeville, the $L_{4.5}N_{67}$ or $L_{6.7}N_{34}$ treatments yielded better than the Std treatment (Tewolde et al., 2007a). This yield performance plus the greater leaf and petiole K concentration of these treatments than the Std treatment at Coffeeville suggests that the 56 kg K ha^{-1} applied to the Std might not have been sufficient for the Std treatment, but the ≥ 4.5 Mg ha^{-1} litter might have supplied sufficient K nutrition. The results from both Cruger and Coffeeville overall suggest that 4.5 Mg ha^{-1} litter supplied sufficient K nutrition for optimum lint yield and fiber quality and that, unlike N, no additional K application was necessary at either location. Earlier reports showed that a litter rate of 4.5 Mg ha^{-1} is insufficient in meeting the N need of cotton and that this rate should be supplemented with about 67 kg ha^{-1} inorganic N fertilization for optimum lint yield (Tewolde et al., 2007a).

Comparisons of petiole K concentration against published sufficiency ranges confirmed that litter as low as 4.5 Mg ha^{-1} delivered sufficient amounts of K. Petiole K concentration of the Std treatment fell well above the published critical minimum of 40 g kg^{-1} (Crozier et al., 2004; Mitchell and Baker, 2000) in both years at Cruger (Table 3). Petiole K concentration of the Std at Coffeeville in 2002 was less than the critical minimum in 2002 suggesting the 56 kg K ha^{-1} applied for this treatment at this location was not sufficient for cotton. Previous research in Mississippi indicated that no-till cotton may need to be fertilized with greater K than conventional till cotton (Varco, 2000). Petiole K concentration of the two treatments that resulted in the most consistent yield performance, $L_{4.5}N_{67}$ and $L_{6.7}N_{34}$ (Tewolde et al., 2007a), consistently fell above the published critical minimum of 40 g K kg^{-1} at both Coffeeville and Cruger. This showed fertilizing cotton with ≥4.5 Mg ha^{-1} litter supplied sufficient, or even abundant, K fertilization. Most cotton and other row crop growers find applying 4.5 Mg ha^{-1} poultry litter manageable and are likely to accept such a recommendation, but would be reluctant to apply litter in excess of 4.5 Mg ha^{-1}.

Table 3. Potassium concentration in above-ground plant parts of cotton fertilized with broiler litter with or without supplemental N as UAN at Coffeeville (no-till) and Cruger (conventional-till), MS in 2002 and 2003

Treatment[z]	K concentration (g kg^{-1})											
	Coffeeville., 31 Jul. 2002				Cruger, 25 Jul. 2002				Cruger, 23 Jul. 2003			
	Leaf	Stem	Repro	Petiole	Leaf	Stem	Repro	Petiole	Leaf	Stem	Repro	Petiole
L_0N_0	22.5	15.2	25.4	32.4	20.4	18.2	20.7	48.5	22.5	14.9	16.7	25.8
$L_{2.2}N_0$	18.7	15.8	26.9	37.4	26.7	20.3	21.4	52.4	25.1	18.9	21.0	37.1
$L_{4.5}N_0$	23.3	15.5	26.3	38.1	24.4	21.4	21.9	56.7	27.0	18.6	18.4	36.8
$L_{6.7}N_0$	24.2	16.9	25.9	41.3	26.4	21.8	24.0	59.1	34.6	22.1	18.4	45.7
$L_{2.2}N_{34}$[y]	20.7	17.0	26.1	33.5	24.0	20.4	21.5	57.0	25.0	17.7	19.3	40.3
$L_{4.5}N_{34}$	24.1	16.0	26.9	40.3	26.2	20.8	22.3	59.0	32.7	21.2	17.0	50.8
$L_{6.7}N_{34}$	27.3	19.0	25.5	43.8	27.7	21.3	23.0	61.3	33.4	23.0	19.3	54.7
$L_{2.2}N_{67}$[y]	20.8	16.2	26.4	37.8	23.1	19.4	21.8	58.8	31.2	20.6	19.5	48.3
$L_{4.5}N_{67}$	24.7	17.6	26.3	43.7	24.7	20.8	22.5	59.0	30.9	21.9	21.6	52.9
Std	19.9	16.3	26.0	36.5	21.4	20.4	20.9	61.6	30.3	23.8	20.5	56.3
ANOVA						*P > F*						
L_L[x]	0.018	0.017	0.995	< 0.001	0.02	0.008	0.002	< 0.001	< 0.001	< 0.001	0.0148	< 0.001
N_L	0.745	0.092	0.958	0.081	0.96	0.463	0.835	0.002	0.004	< 0.001	0.0122	< 0.001

[z] Treatment combinations shown as L (litter) and N (UAN-N) with the subscripts representing rates of applied litter (Mg ha^{-1}) or N (kg ha^{-1}). Std = farm standard fertilization.

[y] Supplemental UAN-N rates in 2004 at Cruger were 67 and 135 kg ha^{-1} instead of the 34 and 67 kg ha^{-1} applied in 2002 and 2003.

[x] L_L=Litter linear effect; N_L = UAN-N linear effect.

Table 4. Total K and Mg applied to cotton in 2002 to 2004 at Coffeeville and Cruger, MS. Broiler litter was the only source of applied K and Mg of all litter treatments. Inorganic fertilizers were the source of K for the Std treatment

Treatment[z]	Total applied K (kg ha^{-1})				Total applied Mg (kg ha^{-1})			
	2002	2003	2004	Avg	2002	2003	2004	Avg
Coffeeville								
L_0N_0	0	0	0	0	0	0	0	0
$L_{2.2}N_0$	72	68	71	70	16	14	14	15
$L_{4.5}$ N_0	141	135	146	141	31	29	29	30
$L_{6.7}N_0$	210	232	219	220	47	46	43	45
$L_{2.2}N_{34}$	72	74	69	72	16	15	14	15
$L_{4.5}N_{34}$	143	161	152	152	32	32	30	31
$L_{6.7}N_{34}$	206	207	215	209	46	43	43	44
$L_{2.2}N_{67}$	70	66	71	69	16	13	14	14
$L_{4.5}N_{67}$	143	164	148	151	32	32	29	31
Std	56	75	112	81	0	0	0	0
Cruger								
L_0N_0	0	0	0	0	0	0	0	0
$L_{2.2}N_0$	58	67	69	64	11	13	14	13
$L_{4.5}$ N_0	111	116	161	129	20	23	32	25
$L_{6.7}N_0$	150	184	231	188	27	37	46	37
$L_{2.2}N_{34}$[y]	65	60	76	67	12	12	15	13
$L_{4.5}N_{34}$	108	111	160	127	20	23	32	25
$L_{6.7}N_{34}$	164	172	224	187	30	35	44	36
$L_{2.2}N_{67}$[y]	54	65	75	65	10	13	15	13
$L_{4.5}N_{67}$	108	108	160	125	20	22	32	24
Std	140	98	93	110	0	0	0	0

[z] Treatment combinations shown as L (litter) and N (UAN-N) with the subscripts representing rates of applied litter (Mg ha^{-1}) or N (kg ha^{-1}). Std = farm standard fertilization.

[y] Supplemental UAN-N rates in 2004 at Cruger were 67 and 135 kg ha^{-1} instead of the 34 and 67 kg ha^{-1} applied in 2002 and 2003.

Relationship of K Concentration with Lint Yield and Fiber Quality. Concentration of K in petioles seems to reflect the amount of applied litter-derived K or inorganic K better than K concentration in bulk leaves, stems, or reproductive parts. Petiole K concentration consistently increased with increasing rate of applied litter. Concentration of K in bulk plant parts also increased with increasing litter rate, but less consistently than K concentration in petioles. Regression analysis of all data showed that petiole K concentration was significantly correlated with lint yield and fiber quality ($Y = 411 - 21.4K_p$, $R^2 = 0.74$, $P < 0.0001$, n = 110 where Y = yield in kg ha^{-1} and K_p = petiole K concentration in g kg^{-1}), but this does not necessarily show that the yield increase can be attributed to increasing petiole K concentration alone.

Of the three location-years, lint yield was highest in 2002 at Cruger (Tewolde et al, 2007a). Petiole K concentration was also greatest in 2002 at Cruger suggesting that the better K nutrition in 2002 at Cruger might have been a contributing factor to the better yield in this year-location. This response is consistent with other findings in which cotton was fertilized with inorganic K (Cassman et al., 1990; Mullins et al., 1997).

Similar to lint yield, fiber length also correlated with petiole K concentration ($L_f = 24.1 + 0.072\ K_p$, $R^2 = 0.58$, $P < 0.0001$, n = 110 where L_f = fiber length in mm) but the correlation was weaker than with lint yield. Unlike lint yield and fiber length, which were positively correlated with petiole K, micronaire and fiber strength were negatively correlated with petiole K concentration ($MIC = 6.0 - 0.0195\ K_p$, $R^2 = 0.41$, $P < 0.0001$, n = 110 and $STR = 31.4 - 0.071\ K_p$, $R^2 = 0.21$, $P < 0.0001$, n = 110). The decrease of micronaire from ≥ 5.0 to the base quality standard of 4.3 to 4.9 is desirable. The lack of positive correlation of fiber strength with petiole K concentration, however, is undesirable and unexpected. We expected better K nutrition would lead to stronger fiber. Our results are similar to those of Pettigrew et al. (1996) who showed data indicating less fiber strength with, than without, fertilizer K application. Unlike our results and those of Pettigrew et al. (1996), others reported small increases in fiber strength with inorganic K application relative to no K application (Cassman et al., 1990; Gormus, 2002; Minton and Ebelhar, 1991). Additional investigations are needed to determine whether K fertilization affects fiber strength and resolve these conflicting findings.

End-of-Season Total K Uptake. End-of-season K uptake by all above-ground plant parts ranged between 86 and 187 kg K ha^{-1} at Coffeeville and between 102 to 260 kg K ha^{-1} at Cruger during the 3 yr (Fig. 1, Table 5). Much of the total K uptake (≈71%) was recovered in burs, stems, and leaves. An average across treatments, years, and locations of about 35, 22, and 14% of the total K uptake (139 kg ha^{-1} at Coffeeville and 193 kg ha^{-1} at Cruger) was recovered in burs, stems, and leaves, respectively. This fraction normally is returned to the soil after harvest and becomes part of the soil K pool available for plant uptake in subsequent seasons. An average of 29% of the total K uptake was recovered in seed (19.5%) and lint (9.5%). Up to 50 kg K ha^{-1} at Coffeeville and 60 kg K ha^{-1} at Cruger was recovered in seed and lint. This fraction represents the total K that is removed from the field with the harvested crop. Others reported similar partitioning of K into the harvested crop (Halevy et al., 1987; Mullins and Burmester, 1990), which suggests the fraction of the total K uptake that is removed from the field at harvest might remain the same across different production conditions.

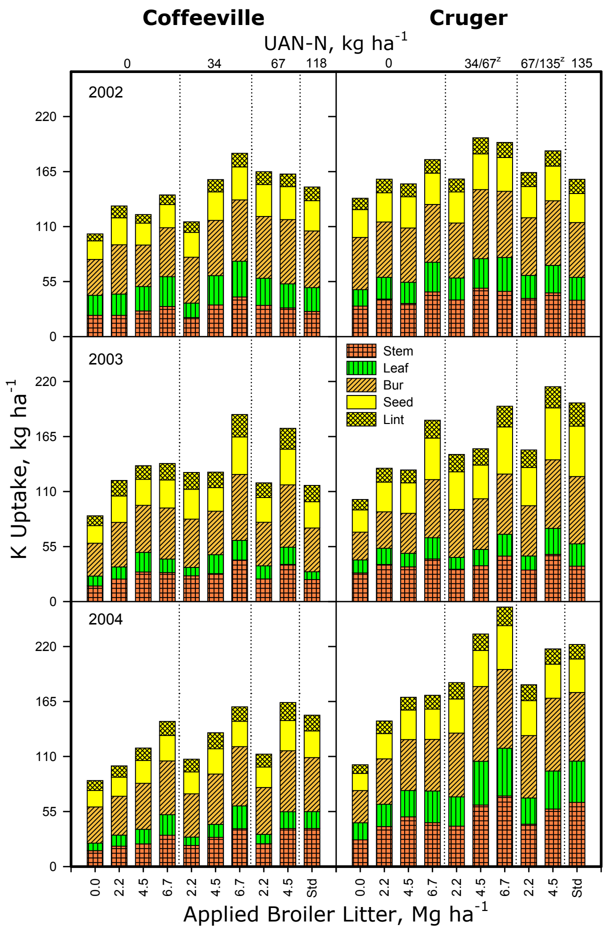

Figure 1. End-of-season total K uptake by above-ground plant parts of cotton grown with broiler litter with or without supplemental N as UAN at Coffeeville, MS (no-till) and Cruger, MS (conventional-till) from 2002 to 2004. ᶻApplied UAN-N rates in 2004 at Cruger were 67 and 135 kg ha^{-1} instead of the 34 and 67 kg ha^{-1} applied in 2002 and 2003.

Table 5. Statistical significance ($P > F$) of the linear effect of applied broiler litter (L_L) or N as urea-ammonium nitrate solution (N_L) on end-of-season K and Mg uptake by above-ground plant parts of cotton grown at Coffeeville (no-till) and Cruger (conventional-till) in Mississippi in 2002 to 2004 (data shown in Figs. 1 and 3). Only the linear effects are shown as the interaction between $L_L \times N_L$ were not significant at $P < 0.05$

Location	Year	Effect	Potassium						Magnesium					
			Leaf	Stem	Bur	Seed	Lint	Total	Leaf	Stem	Bur	Seed	Lint	Total
								P > F						
Coffeeville	2002	L_L	0.021	0.002	0.016	0.064	0.144	0.007	0.372	0.041	0.125	0.089	0.170	0.036
		N_L	0.300	0.083	0.002	0.005	0.008	0.007	< 0.001	0.002	0.058	0.004	0.012	0.001
	2003	L_L	0.022	< 0.001	0.003	0.012	0.007	0.001	0.540	0.045	0.001	0.010	0.007	< 0.001
		N_L	0.936	0.047	0.064	0.079	0.029	0.060	0.755	0.258	0.024	0.084	0.028	0.039
	2004	L_L	0.009	0.001	0.004	0.013	0.023	0.001	0.512	0.087	0.021	0.045	0.021	0.028
		N_L	0.123	< 0.001	0.005	0.011	0.006	0.001	0.975	0.001	0.083	0.025	0.007	0.016
Cruger	2002	L_L	<0.001	0.002	0.017	0.005	0.003	< 0.001	0.025	0.053	0.133	0.019	0.043	0.006
		N_L	0.026	0.126	0.161	0.210	0.008	0.042	0.001	0.172	0.564	0.223	0.067	0.007
	2003	L_L	0.058	0.009	< 0.001	< 0.001	0.001	0.002	0.173	0.027	< 0.001	< 0.001	0.001	0.001
		N_L	0.040	0.138	< 0.001	< 0.001	< 0.001	0.001	0.002	0.002	< 0.001	< 0.001	< 0.001	< 0.001
	2004	L_L	0.017	0.057	0.002	0.001	0.006	0.009	0.116	0.147	0.018	0.004	0.005	0.004
		N_L	0.007	0.048	< 0.001	< 0.001	0.001	0.003	< 0.001	0.001	0.001	0.002	0.001	< 0.001

The amount of total K uptake proportionally increased with increasing rates of both litter and UAN-N (Fig. 1, Table 5). Unfertilized cotton removed an average across years of 92 kg ha^{-1} K at Coffeeville and 114 kg ha^{-1} at Cruger. All of the K uptake by this cotton was derived from the soil because the L_0N_0 cotton received no K fertilization. Relative to the L_0N_0 treatment, fertilization with the Std treatment increased K uptake by 47 kg ha^{-1} to an average of 139 kg K ha^{-1} (51%) at Coffeeville and by 79 kg ha^{-1} to 193 kg K ha^{-1} (69%) at Cruger. Fertilization with the litter-only treatments increased K uptake relative to the L_0N_0 treatment to as much as 142 kg K ha^{-1} (54%) at Coffeeville and 177 kg K ha^{-1} (55%) at Cruger when the applied litter was 6.7 Mg ha^{-1} with no supplemental UAN-N. Supplementing the litter with UAN-N further increased uptake. Potassium uptake was greatest when the cotton was fertilized with litter plus UAN-N, the same fertilization treatments that also resulted in the highest lint yield at both locations. Cotton fertilized with the $L_{4.5}N_{67}$ or $L_{6.7}N_{34}$ treatments removed the greatest K at both Coffeeville and Cruger. The $L_{4.5}N_{67}$ treatment removed an average across years of 167 kg K ha^{-1} at Coffeeville and 206 kg K ha^{-1} at Cruger. The $L_{6.7}N_{34}$ treatment removed an average across years of 177 kg K ha^{-1} at Coffeeville and 216 kg K ha^{-1} at Cruger. These two treatments were also among the highest yielding treatments at both locations (Tewolde et al., 2007a). The greater total K uptake by the $L_{4.5}N_{67}$ or $L_{6.7}N_{34}$ treatments compared to the Std treatment, at Coffeeville in particular, was because of greater K concentration in the different plant parts as well as greater above-ground biomass production.

Magnesium

Extractable Soil Magnesium. Immediately before initiating the experiment in 2002, the soil had 21 mg kg^{-1} M3Mg at Coffeeville and 465 mg kg^{-1} M3Mg at Cruger in the 0–0.15 m depth. The growers at both locations did not apply Mg fertilizers.

Litter significantly affected soil M3Mg at Coffeeville but not at Cruger after 3 yr of consecutive litter application (Table 2). When no supplemental UAN-N was applied at Coffeeville, M3Mg increased from 40 mg kg^{-1} for the L_0N_0 treatment to 64 mg kg^{-1} for the $L_{6.7}N_0$ treatment, with similar increasing trends when supplemental UAN-N was applied. Litter did not affect M3Mg at Cruger where the levels were already high (465 mg kg^{-1}) at the start of the experiment. The Std treatment had less soil M3Mg than all treatments that received litter regardless of the rate at Coffeeville but not at Cruger, suggesting litter application as low as 2.2 Mg ha^{-1} may enrich the top soil with Mg when the initial levels are low.

Response of Mg Concentration in Plant Parts to Applied Litter. Concentration of Mg, unlike K concentration, showed little response to litter application in any of the plant parts at Coffeeville or Cruger in 2002, but responded strongly to applied UAN-N at all locations-years (Table 6). Litter-derived Mg applied to the different treatments ranged between 10 and 47 kg ha^{-1} (Table 4), but there was no Mg concentration response to these applications at either location in 2002. This suggests the external supply of Mg in these soils does not affect cotton Mg nutrition as much as the external supply of N. The Std treatment, which received no Mg application but received the highest yearly application of UAN-N at both locations, had the highest Mg concentration in leaves, stems, and petioles in all location-years. The $L_{4.5}N_{67}$ treatment had the next highest tissue Mg concentration, which might be because the next highest UAN-N rate (67 kg ha^{-1}) was applied to this treatment.

Regression and correlation analysis between N and Mg concentration in the different plant parts confirmed that Mg nutrition is related to N nutrition (Fig. 2). Leaf Mg concentration increased with increasing leaf N concentration, and stem Mg concentration increased with increasing stem N concentration at both locations. But, whereas the stem Mg and N concentration relationship from both locations could be modeled by a single equation ($Mg = 0.05 + 0.197N$), the equation describing the relationship between leaf Mg and leaf N concentration at Cruger was different from that at Coffeeville. Leaf Mg concentration at any given level of leaf N concentration was greater at Cruger than at Coffeeville, probably a reflection of the difference in extractable soil Mg level of the two locations (465 mg kg^{-1} M3Mg at Cruger and 21 mg kg^{-1} M3Mg at Coffeeville). Reproductive Mg concentration did not correlate well with reproductive N concentration (data not shown).

Concentration of Mg responded to applied litter in 2003 at Cruger, but this response might be a reflection of the N nutrition more than the effect of applied Mg rate derived from litter. Applied litter had a large effect on tissue N concentration at Cruger in 2003 (Tewolde et al., 2007b). We believe the significant effect of litter on tissue Mg concentration at Cruger in 2003 is a reflection of the strong effect of litter on tissue N. Litter affected leaf and stem N concentration at both locations in 2002 also, but these effects were weaker in 2002 than in 2003 (Tewolde et al., 2007b).

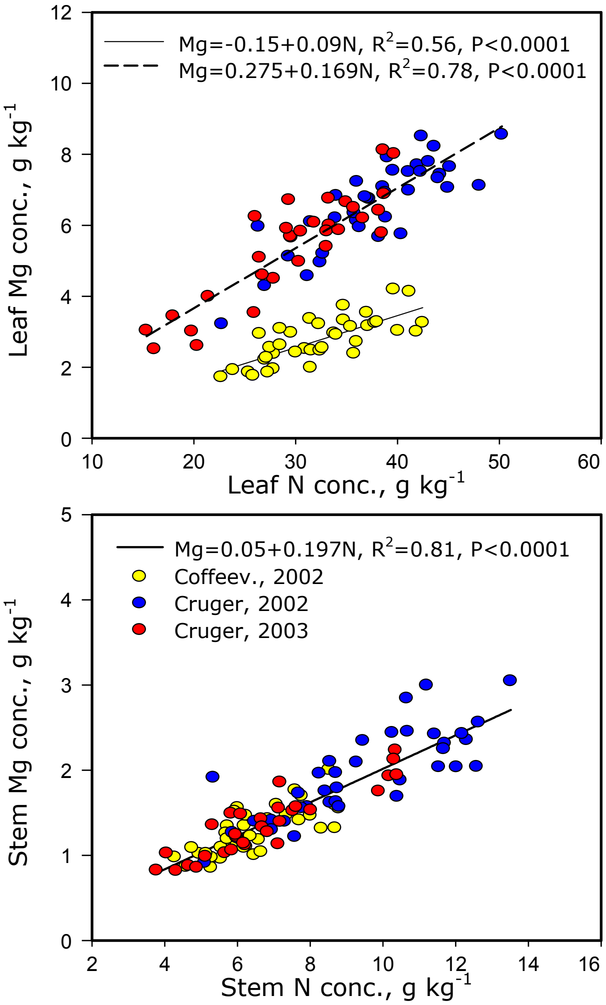

Figure 2. Relationship between N and Mg concentration in bulk leaves and stems of cotton grown with broiler litter with or without UAN-N at Coffeeville, MS (no-till) and Cruger, MS (conventional-till) in 2002 to 2003.

Our finding of the dependence of Mg nutrition on the level of N nutrition is consistent with previous reports on cotton and other crops (Lefsrud et al., 2007; Tewolde et al., 2009). Lefsrud et al. (2007) reported that leaf Mg concentration and chlorophyll concentration of two spinach (*Spinacia oleracea* L.) cultivars grown in a nutrient solution increased with increasing N concentration in the solution and also with increasing tissue N concentration. Tewolde et al. (2009) also reported significant correlations of cotton leaf or stem Mg with N concentration.

One interesting observation of this research is that Mg concentration in reproductive parts relative to Mg concentration in leaves was greater at Coffeeville than at Cruger regardless of the treatment (Table 6). Magnesium concentration in reproductive parts was greater than in leaves of all treatments at Coffeeville. The opposite was true at Cruger where Mg concentration in reproductive parts was much less than in leaves in all treatments. Although the difference between the two locations including tillage might have played a role, it seems the abundance of Mg in soil, leaves, and petioles at Cruger might have inhibited accumulation in reproductive parts. This may have adaptability implications: cotton plants might accumulate Mg in reproductive parts/seed when faced with Mg scarcity in the soil and in leaves as in the case at Coffeeville in 2002.

Sufficiency of Mg Nutrition. Bulk leaf Mg concentration at Coffeeville ranged between 2.3 and 3.4 g kg^{-1} (Table 6). At Cruger, leaf Mg ranged between 5.7 and 7.3 g kg^{-1} in 2002 and between 3.0 to 6.7 g kg^{-1} in 2003. There are no established Mg sufficiency ranges based on bulk plant parts. Mitchell and Baker (2000) compiled published results based on leaf blades and suggested a sufficiency range between 3 and 5 g kg^{-1}. Based on this sufficiency range, only cotton fertilized with the Std or the $L_{4.5}N_{67}$ treatments at Coffeeville had sufficient Mg nutrition. The $L_{4.5}N_{67}$ treatment at this location had the highest lint yield with 1393 kg ha^{-1} (Tewolde et al., 2007a). All other treatments including the Std produced less lint than the $L_{4.5}N_{67}$ treatment, but this might be due to other factors including insufficient N and might not be due to insufficient soil Mg supply alone.

At Cruger, lint yield varied between 1478 kg ha^{-1} for the L_0N_0 treatment to 1718 kg ha^{-1} for the $L_{4.5}N_{67}$ treatment in 2002, and between 928 kg ha^{-1} for the L_0N_0 treatment to 1771 kg ha^{-1} for the Std treatment in 2003 (Tewolde et al., 2007a). However, nearly all treatments in both years had much higher bulk leaf Mg concentration than the sufficiency range described by Mitchell and Baker (2000) based on leaf blades. The treatments that received insufficient litter and UAN-N fertilization had lower yields and less leaf, stem, or petiole Mg concentrations than treatments considered sufficiently fertilized with litter and UAN-N. It appears applying sufficient N fertilization is more important to cotton Mg nutrition in these soils than applying Mg as an external fertilizer. As some previous reports showed (Holland and Mitchell, 2005; McCart and Kamprath, 1965), soils in the mid-south and southeastern US might have sufficient soil Mg for cotton. In Alabama, > 96% of all cotton soil samples submitted to Auburn University's Soil Testing Laboratory had Mg concentrations considered sufficient for cotton (Holland and Mitchell, 2005). The few samples (< 4%) that needed Mg fertilization were usually samples with low pH. Our results suggest that ensuring sufficient N fertilization usually ensures sufficient Mg nutrition of cotton in most if not all mid-south and southeastern US cotton soils whether fertilized with poultry litter or conventional inorganic N.

End-of-Season Total Mg Uptake. Cotton removed as much as 25 kg ha^{-1} Mg at Coffeeville and 45 kg ha^{-1} at Cruger in above-ground plant parts (Fig. 3, Table 5). Both litter and UAN-N had a significant effect on total Mg uptake by cotton. Although litter did not always affect the concentration of Mg in different plant parts, total Mg uptake increased with increasing applied litter rate. This is because total Mg uptake was calculated by multiplying dry weight by Mg concentration and because dry weight increased with increasing rate of applied litter (data not shown). The increase of Mg uptake with increasing UAN-N fertilization is due to increases in Mg concentration and biomass.

Much of the total Mg uptake by above-ground plant parts was in seeds and lint (Fig. 3, Table 5). Nearly 61% of the total 16.5 kg ha^{-1} Mg uptake at Coffeeville and approximately 41% of the total 27.1 kg ha^{-1} uptake at Cruger was in seed and lint, which means much of the plant Mg is exported from the field with harvested seed and lint. This implies the soil Mg reserve could be depleted when growing cotton in the same soil for extended periods without Mg fertilization. As shown in Table 4, even the 2.2 Mg ha^{-1} litter rate supplied sufficient Mg to replace the amount removed with harvested crop. Fertilizing cotton with any amount of litter > 2.2 Mg ha^{-1} likely results in soil Mg accumulation.

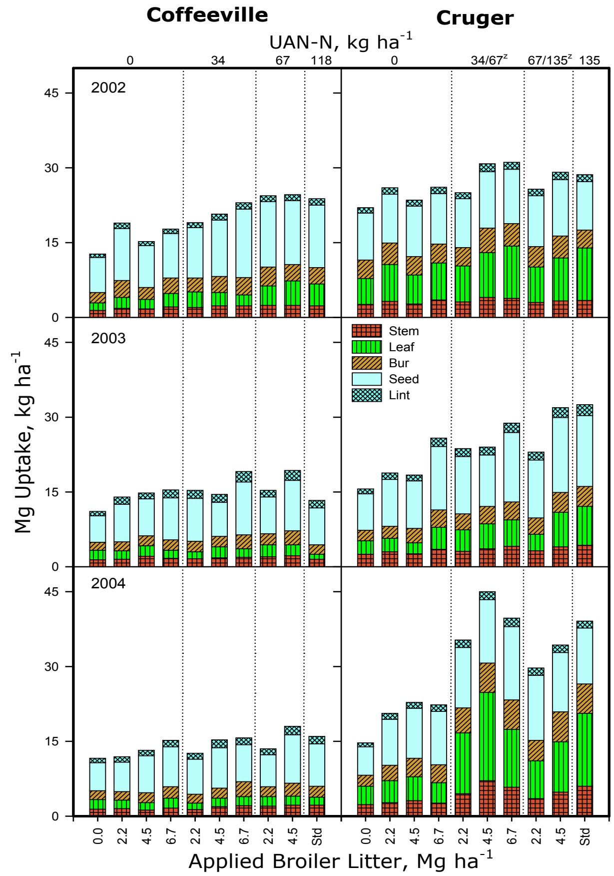

Figure 3. End-of-season total Mg uptake by above-ground plant parts of cotton grown with broiler litter with or without supplemental N as UAN at Coffeeville, MS (no-till) and Cruger, MS (conventional-till) from 2002 to 2004. [z]Applied UAN-N rates in 2004 at Cruger were 67 and 135 kg ha^{-1} instead of the 34 and 67 kg ha^{-1} applied in 2002 and 2003.

Table 6. Magnesium concentration in above-ground plant parts of cotton fertilized with broiler litter with or without supplemental N as UAN at Coffeeville (no-till) and Cruger (conventional-till), MS in 2002 and 2003

Treatment[z]	Mg concentration (g kg^{-1})											
	Coffeeville, 31 Jul. 2002				Cruger, 25 Jul. 2002				Cruger, 23 Jul. 2003			
	Leaf	Stem	Repro	Petiole	Leaf	Stem	Repro	Petiole	Leaf	Stem	Repro	Petiole
L_0N_0	2.34	1.08	4.59	3.57	6.12	1.77	3.9	5.69	2.99	0.89	2.67	4.13
$L_{2.2}N_0$	2.45	1.21	4.86	3.50	5.95	1.61	3.91	5.51	4.09	1.09	3.21	4.96
$L_{4.5}N_0$	2.47	1.11	4.56	3.31	5.74	1.60	3.69	5.57	3.88	1.05	2.89	3.96
$L_{6.7}N_0$	2.68	1.18	4.69	3.46	6.63	1.95	3.93	5.91	6.26	1.26	2.81	5.23
$L_{2.2}N_{34}$[y]	2.81	1.24	4.77	4.06	6.38	1.73	3.74	5.86	5.55	1.20	2.81	5.60
$L_{4.5}N_{34}$	2.78	1.24	4.70	3.53	7.02	2.01	3.99	6.64	5.69	1.33	2.67	6.23
$L_{6.7}N_{34}$	2.84	1.31	4.16	3.61	6.42	1.94	3.49	6.27	6.43	1.66	2.91	6.01
$L_{2.2}N_{67}$[y]	2.88	1.41	4.53	4.15	7.12	1.82	3.96	6.55	5.99	1.64	2.90	6.45
$L_{4.5}N_{67}$	3.16	1.31	4.29	4.58	7.31	2.60	3.81	6.96	6.41	1.53	3.47	6.84
Std	3.37	1.52	4.41	4.69	7.25	2.34	3.83	7.04	6.74	2.04	3.14	6.80
ANOVA					$P > F$							
L_L[x]	0.240	0.592	0.194	0.580	0.295	0.303	0.284	0.297	< 0.001	0.002	0.070	0.120
N_L	0.002	0.002	0.074	0.004	0.001	0.018	0.682	0.001	< 0.001	< 0.001	0.158	0.001

[z] Treatment combinations shown as L (litter) and N (UAN-N) with the subscripts representing rates of applied litter (Mg ha^{-1}) or N (kg ha^{-1}). Std = farm standard fertilization.

[y] Supplemental UAN-N rates in 2004 at Cruger were 67 and 135 kg ha^{-1} instead of the 34 and 67 kg ha^{-1} applied in 2002 and 2003.

[x] L_L = Litter linear effect; N_L = UAN-N linear effect.

CONCLUSION

Our research showed that cotton absorbed K in direct proportion to the rate of applied litter and that ≥ 4.5 Mg ha^{-1} litter supplied sufficient to abundant K for optimum lint yield. Although litter contains approximately the same percent N as K, the 4.5 Mg ha^{-1} litter was previously found to be insufficient to meet the N need of cotton (Tewolde et al., 2007a), indicating that litter K is more readily available for plant uptake than litter N. Much of the total K uptake (≈71%) was recovered in burs, stems, and leaves and is returned to the soil after harvest and becomes part of the soil K pool potentially available for plant uptake in subsequent seasons. Only 29% of the total K uptake was recovered in seed and lint and represents the fraction of the total K that is removed from the field at harvest. Unlike K, Mg concentration in plant parts did not respond to litter application rate unless litter also affected N concentration. Concentration of Mg responded strongly to applied UAN-N suggesting that cotton Mg nutrition depends on the level of N fertilization more than the level of Mg application. Much of the total Mg uptake by above-ground plant parts was recovered in seeds and lint. About 40 to 60% of the total Mg uptake was recovered in seed and lint, which means about half of the Mg uptake is exported from the field at harvest. Our results show that K nutrition of cotton depends on the rate of applied litter, whereas Mg nutrition is dependent on whether the cotton received sufficient N fertilization.

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