Reprinted from *Crop Science*
Vol. 36, No. 4

Fertilizer ^{15}Nitrogen Recovery by Corn, Wheat, and Cotton Grown with and without Pre-Plant Tillage on Norfolk Loamy Sand

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ABSTRACT

Cropping systems must efficiently use N inputs to be sustainable environmentally and economically. This research was conducted to determine the fate of ^{15}N fertilizer that was applied to corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), or cotton (*Gossypium hirsutum* L.) grown in a 2-yr, three-crop rotation on Norfolk (Typic Kandiudult) loamy sand. A total of 48, 2.3- by 2.3-m microplots were established, half into plots that received surface tillage (disked) and half into non-disked plots. Corn and wheat received a split application of urea [$CO(NH_2)_2$] plus ammonium nitrate (NH_4NO_3) solution (UAN) that had a 5 atom percent (ATM%) ^{15}N isotopic label. Cotton was fertilized with NH_4NO_3 containing a 5 ATM% label. The amounts of ^{15}N removed in the harvested portion of treated and subsequent crops, recycled in crop residues, or remaining in the upper 90 cm of the soil profile were determined. Corn, wheat, and seed cotton yields ranged from 1485 to 7410, 1850 to 2270, and 120 to 2510 kg ha^{-1}, respectively, with significant differences caused primarily by seasonal rainfall or temperature extremes. No-till significantly increased cotton yield, presumably because of water conservation. Crop removal accounted for 20 to 34% of the fertilizer ^{15}N, while another 20% was accounted for by soil profile analysis to a depth of 90 cm. Approximately 50% of the ^{15}N was apparently lost through denitrification, volatilization, or leaching below the root zone. Most of this loss appeared to occur during the cropping season in which the ^{15}N was applied. This suggests that for optimum fertilizer efficiency and environmental sustainability, crop production practices on Coastal Plain soils must account for all N sources that plants can draw upon, and should accommodate several fertilizer N management options including split applications, injection beneath the soil surface, and/or using less mobile forms.

CROP USE of fertilizer N is often quite low, as demonstrated by several ^{15}N studies that report recoveries of 9 to 65% (Bijeriego et al., 1979; Olson, 1980; Kitur et al., 1984; Meisinger et al., 1985; Sanchez and Blackmer, 1988; Timmons and Cruse, 1990; and Reddy and Reddy, 1993). Fertilizer is just one N source that crops can draw upon, but since substantial amounts are used each year, tracing its fate is important for improving profitability and protecting the environment.

Quantifying the fate of fertilizer N is especially important for coarse textured Atlantic Coastal Plain soils. Their low organic matter and total N concentrations make N fertilizer applications essential for crop production, while high annual rainfall can result in substantial N loss through leaching, denitrification, or both. Nitrogen recovery by crops grown on these soils can also be reduced because subsoil acidity and near-surface compaction often restricts plant rooting to a depth of 1 m or less.

The use of ^{15}N is recognized as a valuable tool for determining the fate and behavior of fertilizer N (Hauck and Bremner, 1976). Compared with non-tracer studies, determinations of labeled fertilizer N can be made more accurately, treatment effects can be detected with greater sensitivity (Russelle et al., 1981), and studies of transformations and fate of fertilizer N can be conducted without a check plot (Hauck and Bremner, 1976). However, data interpretation must proceed cautiously because of mineralization-immobilization turnover (MIT) reactions (Jansson and Persson, 1982; Walters and Malzer, 1990). MIT reactions can also cause estimates of fertilizer use efficiencies to be lower than those calculated by difference (Terman and Brown, 1968; Westerman and Kurtz, 1974; Dowdell and Webster, 1980; Varvel and Peterson, 1990; and Torbert et al., 1992).

Tillage practices have been reported to affect N leaching (Tyler and Thomas, 1977), denitrification (Olson et al., 1979), and immobilization (Gilliam and Hoyt, 1987). Torbert and Reeves (1994) evaluated effects of tillage and wheel traffic on ^{15}N recovery by cotton grown in a double-crop rotation with wheat on a thermic Typic Hapludult complex in Alabama. Their highest fertilizer N recovery, which occurred in a year with above-normal rainfall, was 35%. They concluded that most N uptake response to tillage and traffic was caused by changes in native soil N and not to the dynamics of fertilizer N.

Most ^{15}N studies have been limited to a single crop, even if recovery was measured within a rotation (Varvel and Peterson, 1990; Torbert and Reeves, 1994). Sanchez and Blackmer (1988) reported that second and third consecutive corn crops recovered 0.3 to 1.5% of the ^{15}N, but apparently, there have been few attempts to follow ^{15}N through sequential crops grown in rotation. Our objective was to measure ^{15}N fertilizer recovery through a 2-yr, non-irrigated, corn and wheat-cotton double-crop rotation grown with and without surface tillage on Norfolk loamy sand in the southeastern Atlantic Coastal Plain.

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Published in Crop Sci. 36:975–981 (1996).

Abbreviations: ATM%, atom percent; A_p, mineral horizon with properties resulting from tillage; E, mineral horizon characterized by its loss of silicate clay, iron, and aluminum; MIT, mineralization-immobilization and turnover; KMC, Kelly Manufacturing Company; UAN, urea-ammonium nitrate; lfs, loamy fine sand; scl, sandy clay loam

Table 1. Characteristics of Norfolk loamy sand where crop sequence and tillage effects on ^{15}N fertilizer recovery were evaluated.

Horizon (texture)†	Depth	Sand	Silt	Clay	pH	CEC	Bulk density	Total C	Extractable P	Extractable K
	cm	g kg^{-1}				cmol$_c$ kg^{-1}	g cm^{-3}	g kg^{-1}		
A_p (LFS)	0 to 20	787	185	28	6.0	1.8	1.60	5.54	53	71
E (LFS)	20 to 40	732	244	24	5.7	1.8	1.70	3.20	7	66
B_t (SCL)	40 to 90	517	175	308	5.2	3.9	1.55	2.27	4	87

† LFS - loamy fine sand; SCL - sandy clay loam.

METHODS AND MATERIALS

Site Characteristics

This study was conducted on a 2.76-ha site that was established in 1979 at the Pee Dee Research and Education Center near Florence, SC. Coordinates are 34° 18′ N, 79° 44′ W, and the elevation is 37 m above mean sea level. There were five, 92- by 60-m replicates. Commercial, six-row farm equipment was used for all tillage and planting operations. Soil characteristics are presented in Table 1.

Experimental Design

The five field replicates were split once for crop sequence (Rotation I or II) and a second time for tillage (disked vs non-disked). This created 20 tillage plots that were 23 m wide and 60 m long arranged in a split-split plot experimental design. Three 2.3- by 2.9-m ^{15}N microplots were established in the center of each tillage block within four of the five field replicates. This created 48 microplots with dimensions that exceeded the 1.5-by 1.5-m minimum size suggested by Follett et al. (1991) for field studies with wheat. The first eight microplots (Microplots 1–8) were established when corn was planted into Rotation I in March of 1988 (Table 2). Microplots 9 through 16 were established when wheat was planted in November 1988 following the corn crop. Microplots 17 through 24 were initiated when cotton was planted following wheat harvest in June 1989. The fourth, fifth, and sixth sets of microplots (Microplots 25–32, 33–40, and 41–48) were established in Rotation II starting with corn in 1989.

Recovery of ^{15}N fertilizer was measured by harvesting and analyzing the plant material from the first crop grown on each microplot after the one-time application of labeled fertilizer. Residual ^{15}N fertilizer recovery was determined by measuring the amount of ^{15}N accumulated by each successive crop. The data for each crop were analyzed by means of a SAS general linear model (SAS, 1985). Year or rotation block was analyzed by evaluating data from Microplots 1 through 8 vs 25 through 32 (^{15}N applied to corn), 9 through 16 vs 33 through 40 (^{15}N applied to wheat), and 17 through 24 vs 41 through 48 (^{15}N applied to cotton) with a year by replicate error term. Tillage effects and year by tillage interactions were evaluated by the residual error.

Field Operations

The cropping history before this study was initiated included corn on all plots during 1979, 1980 and 1981; a corn and wheat-soybean [*Glycine max* (L.) Merr.] double-crop rotation from 1982 through 1986; and a year of chemical-fallow with glyphosate [isopropylamine salt of *N*-(phosphonomethyl)glycine] for weed control in 1987. Disk-tillage resulted in the incorporation of crop residues, fertilizers, and lime. These materials were not incorporated on non-disked plots. When row-crops (corn or cotton) were planted, both tillage treatments received in-row subsoiling with a Kelly [Kelly Manufacturing Co. (KMC), Tifton, GA][1] subsoiler to fracture a root restrictive layer (E horizon) that reforms annually within these soils (Busscher et al., 1986).

Corn (cv. Pioneer Brand 3165) was planted during the last week of March at a seeding rate of 5.5 seed m^{-2} in 76-cm rows with Case-International (Case-International Corporation, Racine, WI) Model 800 planters. After harvesting the corn, wheat (cv. Coker 9227) was sown in mid-November at a rate of 100 kg ha^{-1} in 18-cm rows with a KMC no-till grain drill (1988 and 1989) or a John Deere (Deere & Co., Inc., Moline, IL) model 750 no-till drill (1990–present). Cotton (cv. Pee Dee 1) was planted with the Model 800 planters following wheat harvest in early June. Rows were spaced 96 cm apart and the seeding rate was 14 seed m^{-2}.

Corn received 34 kg N ha^{-1} at planting and an additional 134 kg N ha^{-1} at the V8 growth stage. A urea plus ammonium-nitrate solution (UAN) with a 5% ^{15}N label was banded along each corn row within the microplots, while the remainder of the field received a banded application of commercial UAN liquid fertilizer. Wheat was fertilized with 50 kg N ha^{-1} at planting and sidedressed with 67 kg N ha^{-1} at Feekes Growth Stage 3. The ^{15}N labeled UAN solution was sprinkled uniformly over each microplot with approximately 20 L of water. Cotton received 28 kg N ha^{-1} at planting plus 56 kg N ha^{-1} when the first squares were forming. The ^{15}N source was granular NH_4NO_3 with a 5% label. These fertilizer materials and rates provided a total ^{15}N application of 8.40, 5.85, and 4.20 kg ^{15}N ha^{-1} to corn, wheat, and cotton crops, respectively. Mi-

[1] Mention of trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

Table 2. Crop sequence and ^{15}N application time for each of the six micro-plot sets established in disked and non-disked treatments on Norfolk loamy sand.

Plot no.	1988	1989	1990	1991	1992
1 to 8	corn†	wheat/cotton	corn	wheat/cotton	corn
25 to 32	wheat/cotton	corn†	wheat/cotton	corn	wheat/cotton
9 to 16	corn	wheat†/cotton	corn	wheat/cotton	corn
33 to 40	wheat/cotton	corn	wheat†/cotton	corn	wheat/cotton
17 to 24	corn	wheat/cotton†	corn	wheat/cotton	corn
41 to 48	wheat/cotton	corn	wheat/cotton†	corn	wheat/cotton

† Application of ^{15}N fertilizer.

Table 3. Year and surface tillage effects on microplot crop yield on Norfolk loamy sand.

Year	Corn		Wheat		Seed cotton	
	Disked	Non-disked	Disked	Non-disked	Disked	Non-disked
	kg ha^{-1}					
1988	3635	3870	–	–	–	–
1989	6970	5870	2150	2270	1770	1860
1990	1485	1900	1910	1850	1310	1410
1991	7410	7060	1940	2870	1695	2510
1992	–	–	2100	1295	120	245
$P > F$						
Year (Yr)	0.0001		0.0323		0.0001	
Tillage (Till)	0.4093		0.7026		0.0204	
Yr × Till	0.1481		0.0015		0.0811	

croplots that were to receive ^{15}N for any phase of the rotation were covered with canvas while fertilizer N was applied to the rest of the field, including microplots where residual ^{15}N effects were to be measured. The "disk-tillage" within the microplots was done with a garden tiller to prevent contamination or dilution with untreated soil.

Plant and Soil Sampling

Plant samples were collected from the center 2.4 m^2 of each microplot to measure ^{15}N recovery (total uptake) or removal by the grain or cotton bolls. After shelling corn or threshing wheat, cobs and straw were returned and spread uniformly across each microplot. During field harvest, microplots were covered to prevent contamination with residues from outside of the treated area.

After each crop was harvested, soil samples were collected approximately 0.9 m diagonally from the corner of each microplot to avoid disturbing the integrity of the center areas where crop samples were collected. This distance was assumed to be sufficient to avoid border effects since it exceeded the 0.76-m minimum recommended by Follett et al. (1991).

Plant and soil samples were ground and subsampled before submitting them for ^{15}N analysis. Samples were reground with a Spex model 8000 mixer-mill (Spex Industries, Inc., Edison, NJ). The grinding vessels were washed with distilled water and rinsed with ethanol to minimize cross-contamination between samples. Total N was measured with a Carlo Erba model NA 1500 automatic N analyzer. A Europa Scientific Ltd. (Crewe, Cheshire, UK) Tracermass stable isotope mass spectrometer, interfaced with the Carlo Erba, was used to measure the ^{14}N and ^{15}N atom percent (Schepers et al., 1989).

Fertilizer ^{15}N recovery was determined by measuring yield, total N concentration, and the ^{15}N ATM% in the portion of the crop that was removed from each microplot (i.e. corn grain, wheat grain, and cotton lint plus seed). The natural ATM% ^{15}N, which averaged 0.3715 at this site, was subtracted from the ATM% measured in each crop fraction. The percent fertilizer ^{15}N recovery was computed by dividing removal values by the amount that was applied to a specific microplot.

Residual fertilizer ^{15}N to a depth of 90 cm within the soil profile was calculated for each sampling date by multiplying total N concentration and ATM% ^{15}N in samples from seven depth increments (0–5, 5–10, 10–15, 15–30, 30–45, 45–60, and 60–90 cm) and subtracting background levels of ^{15}N. Bulk densities for the seven depth increments were obtained from an unpublished data set collected for various soil profile depths in 12 soil pits that had been dug at the experimental site (personal communication, 1994, W.J. Busscher).

RESULTS AND DISCUSSION

Crop Yields

The effects of year (Rotation I vs II) and surface tillage (disked vs non-disked) on crop yield from the ^{15}N microplots are presented in Table 3. Corn yield in 1989 and 1991 was consistent with anticipated non-irrigated yields (USDA-SCS, 1979). Yields were reduced in 1988 because of a severe drought that occurred during silking, while in 1990, yield was depressed by low rainfall throughout the growing season (518 mm compared with a 5-yr mean of 728 mm). Production practices for wheat were similar to those reported by Karlen and Gooden (1987), but grain yields were lower than expected. Double-crop seed cotton yields which averaged 1770 kg ha^{-1} for 1989, 1990, and 1991, were reasonable for the southeastern USA (Lee, 1984). They were also similar to the 2-yr average of 1942 kg ha^{-1} reported by Tobert and Reeves (1994) for cotton crops grown in Alabama when rainfall was low (1990) or above normal (1991). The most consistent and statistically significant factor

Table 4. Rainfall and temperature data from the Pee Dee Research and Education Center near Florence, SC. The 5-yr mean is for 1988-1992, while the 22-yr mean is for 1971-1992.

Month	1988	1989	1990	1991	1992	5-yr mean	22-yr mean
	Monthly rainfall (mm)						
January	107	52	65	137	85	89	83
February	39	55	48	46	66	51	90
March	61	146	69	169	67	102	103
April	96	142	28	22	30	64	77
May	81	76	82	77	94	82	78
June	65	109	25	86	153	88	123
July	184	131	135	152	26	126	150
August	95	161	170	146	357	186	120
September	143	159	25	42	55	85	100
October	42	71	260	22	105	100	66
November	53	65	50	75	168	82	51
December	11	134	58	43	105	70	69
TOTAL	977	1301	1015	1017	1311	1124	1109
	Average air temperature (°C)						
January	3.7	8.8	10.8	7.9	7.4	7.7	7.1
February	7.1	9.1	12.6	9.9	9.8	9.7	8.4
March	11.9	12.3	14.4	13.8	11.4	12.8	12.2
April	16.4	15.9	16.4	18.7	16.4	16.4	17.3
May	20.8	20.3	22.2	23.6	19.5	21.3	21.7
June	24.4	26.5	26.1	25.6	23.7	25.3	25.2
July	28.8	26.9	28.2	28.0	28.7	28.2	26.8
August	27.5	25.6	27.3	26.3	25.6	26.5	26.4
September	21.6	23.1	23.2	23.4	23.4	22.9	23.5
October	12.8	17.9	19.3	17.6	15.9	16.7	17.9
November	11.1	13.1	13.4	11.1	12.7	12.3	12.4
December	6.9	3.4	10.9	9.0	7.5	7.5	8.4

Table 5. Tillage and year effects on total-N, NH_4-N, and NO_3-N at three depths in Norfolk loamy sand before and at three dates after microplot establishment.

Months after establishment	Year	Total N Disked	Total N Nondisk	NH_4-N Disked	NH_4-N Nondisk	NO_3-N Disked	NO_3-N Nondisk
		kg ha⁻¹					
		0 to 5 cm					
0 (Mar.)	1988	264	494	4.8	0.6	2.9	4.9
	1989	264	526	1.8	2.3	7.4	8.0
Year		NS†		NS		***	
Tillage		***		NS		*	
Year × Tillage		NS		NS		NS	
6 (Oct.)	1988	349	575	5.1	4.5	2.9	4.8
	1989	254	651	0.6	0.4	2.5	6.9
Year		NS		NS		NS	
Tillage		***		NS		***	
Year × Tillage		NS		NS		NS	
15 (June)	1989	427	610	1.8	2.3	7.4	8.0
	1990	306	639	0.3	1.2	2.8	2.6
Year		NS		**		***	
Tillage		***		**		NS	
Year × Tillage		NS		NS		NS	
24 (Mar.)	1990	451	462	1.7	1.5	2.8	3.2
	1991	291	686	13.0	13.0	1.8	1.8
Year		NS		***		***	
Tillage		***		NS		NS	
Year × Tillage		**		NS		NS	
		5 to 10 cm					
0 (Mar.)	1988	190	308	1.6	1.1	0.5	3.0
	1989	260	245	1.0	1.4	5.5	4.0
Year		NS		NS		**	
Tillage		NS		NS		NS	
Year × Tillage		*		NS		**	
6 (Oct.)	1988	276	241	3.2	5.9	2.0	2.1
	1989	223	285	0.3	0.2	1.8	3.3
Year		NS		*		NS	
Tillage		NS		NS		NS	
Year × Tillage		NS		NS		NS	
15 (June)	1989	331	338	1.0	1.4	5.5	4.0
	1990	203	218	0.1	0.7	1.6	1.0
Year		**		NS		**	
Tillage		NS		NS		NS	
Year × Tillage		NS		NS		NS	
24 (Mar.)	1990	365	239	1.9	1.1	2.4	2.6
	1991	213	233	15.6	15.1	1.8	1.5
Year		*		***		NS	
Tillage		NS		NS		NS	
Year × Tillage		NS		NS		NS	
		10 to 15 cm					
0 (Mar.)	1988	169	217	4.1	0.0	0.3	1.4
	1989	257	182	1.6	2.3	3.7	3.5
Year		NS		NS		***	
Tillage		NS		NS		NS	
Year × Tillage		NS		*		NS	
6 (Oct.)	1988	194	173	5.8	2.6	2.0	1.5
	1989	230	188	0.3	0.3	2.2	2.1
Year		NS		NS		NS	
Tillage		NS		NS		NS	
Year × Tillage		NS		NS		NS	
15 (June)	1989	238	248	1.6	2.3	3.7	3.5
	1990	178	136	0.4	0.8	1.4	0.7
Year		**		NS		***	
Tillage		NS		NS		NS	
Year × Tillage		NS		NS		NS	
24 (Mar.)	1990	233	207	0.8	1.1	2.5	2.5
	1991	221	167	8.0	17.4	2.2	2.0
Year		NS		**		NS	
Tillage		NS		***		NS	
Year × Tillage		NS		***		NS	

† NS, *, **, and *** denote no statistical significance, or significance at the 0.1, 0.05, and 0.01 probability levels.

affecting these yields was year. In general, this was directly related to the amount of rainfall received during the various growing seasons (Table 4), although the low cotton yield in 1992 was caused by abnormally low temperatures which occurred before the crop was mature.

Preplant tillage did not affect corn and wheat yields, but reduced cotton yields. Seedbed water content and seedling emergence were not measured, but disking presumably increased water loss and further delayed a crop, that because of double-cropping, was already facing a short growing season. This explanation is consistent with unpublished observations by farmers and crop advisors that water conservation associated with conservation tillage and rapid seedling emergence are important for successful double-crop cotton production at this latitude.

The year × tillage interaction was not significant for corn production, but it was highly significant for wheat. In both 1989 and 1990, preplant tillage had minimal effect on wheat yield. In 1991, however, no-till decreased yield more than 800 kg ha^{-1}, while in 1992, the reverse occurred. The interaction for cotton was significant at $P \leq 0.1$, presumably because of large yield differences in 1991.

As a final assessment of yield effects for 1988 through 1992, Pearson correlation coefficients were computed to compare microplot yield with that for the entire 23-m by 60-m tillage plots. The values averaged 0.926, 0.754, and 0.825 for corn, wheat, and cotton, respectively. Higher microplot yields for all crops were probaby the result of less spatial variability and hand-harvesting of the microplots compared with machine harvesting of the entire tillage plots.

Soil Nitrogen Levels

Periodic measurements to a depth of 90 cm for all 48 microplots showed that NH_4-N ranged from 5 to 57 kg ha^{-1}; NO_3-N ranged from 4 to 57 kg ha^{-1}; and total-N ranged from 1300 to 2125 kg ha^{-1}. Statistical analyses of total-N data by sampling depth consistently showed significant differences between disked and non-disked treatments in the 0- to 5-cm increment. The result was similar for all 48 microplots and all sampling dates, so for brevity, Table 5 contains data from only selected samplings of microplots established in the corn phase of both rotation cycles. As expected, this response for total-N was consistent with the C data reported by Hunt et al. (1996). Together, the N and C results emphasize that changes in near-surface soil properties are a primary effect of conservation tillage, even for sandy Coastal Plain soils. There were some statistically significant differences due to year and tillage for NH_4-N and NO_3-N in the upper 15 cm (Table 5) and within the upper 90 cm of the soil profile, but in general, the amounts were similar and quite low. In samplings that followed crops with low yield because of drought, residual amounts of NH_4-N (Table 5, March 1991) and occasionally NO_3-N (data not shown) were slightly higher than when samples were collected following periods of normal rainfall.

^{15}Nitrogen Balance

The amounts of fertilizer ^{15}N removed with the harvested portion of each crop, taken up by the crop and returned with the crop residues, or detected within the upper 90 cm of the soil profile in the microplots established for each of the crops grown in the 2-yr rotation are presented in Tables 6, 7, and 8. In general, because of rainfall or temperature effects on crop yield, year

Table 6. Periodic accounting for the 8.4 kg ^{15}N ha^{-1} applied one time to corn growth in a 2-yr, three-crop rotation on Norfolk loamy sand.

Months after applying ^{15}N (month)	Year	Harvested crop	^{15}N removed with harvested crop		^{15}N remaining in crop residue		^{15}N measured in 90-cm soil profile	
			Disked	Nondisk	Disked	Nondisk	Disked	Nondisk
			kg ha^{-1}					
6 (Oct.)	1988	Corn	1.57	1.67	1.94	1.58	1.81	1.78
6 (Oct.)	1989		2.28	1.60	0.98	0.91	1.19	1.65
Year			NS†		**		NS	
Tillage			**		NS		NS	
Year × Tillage			**		NS		NS	
14 (June)	1989	Wheat	0.36	0.42	0.28	0.36	2.17	2.32
14 (June)	1990		0.27	0.26	0.10	0.13	1.50	1.44
Year			*		***		*	
Tillage			NS		*		NS	
Year × Tillage			NS		NS		NS	
20 (Dec.)	1989	Cotton	0.34	0.33	0.32	0.32	1.65	1.85
20 (Dec.)	1990		0.14	0.11	0.28	0.20	1.03	1.16
Year			***		***		NS	
Tillage			NS		NS		NS	
Year × Tillage			NS		NS		NS	
30 (Oct.)	1990	Corn	0.08	0.12	0.00	0.00	1.28	2.30
30 (Oct.)	1991		0.45	0.37	0.35	0.49	–‡	–
Year			***		***		–	
Tillage			NS		NS		*	
Year × Tillage			**		*		–	
38 (June)	1991	Wheat	0.21	0.28	0.07	0.13	1.52	1.88
38 (June)	1992		0.21	0.18	0.06	0.07	–	–
Year			*		**		–	
Tillage			NS		**		NS	
Year × Tillage			NS		NS		–	

† NS, *, **, and *** denote no statistical significance, or significance at the 0.1, 0.05, and 0.01 probability levels.
‡ ^{15}N measurements were not made on soil samples collected from Rotation II.

or rotation block resulted in most of the statistically significant differences. Out of 12 comparisons, tillage showed significant effects twice for crop removal of ^{15}N and three times for crop residue and soil profile measurements, respectively.

Soil profile measurements made before the labeled fertilizer was applied showed a background ATM% ^{15}N that ranged from 0.3705 to 0.3726 and averaged 0.3715 ($\pm$0.0009) throughout the upper 90 cm. This average is slightly higher than the 0.3663 ATM% ^{15}N accepted for atmospheric N_2, but it is within the range reported for various soils by Cheng et al. (1964) and within the $\pm$2% of atmospheric level that is common for various biosphere components (Shearer and Kohl, 1993). When summed for the upper 90 cm of the soil profile, background levels of ^{15}N ranged from 5 to 6 kg ha^{-1}. The portion of ^{15}N associated with each depth increment was subtracted from the measured amount on each sampling date so that a fertilizer ^{15}N balance could be computed for each crop sequence.

The total amount of fertilizer ^{15}N that could be accounted for by crop removal, when summed for 38, 33,

Table 7. Periodic accounting for the 5.85 kg ^{15}N ha^{-1} applied one time to wheat grown in a 2-yr, three-crop rotation on Norfolk loamy sand.

Months after applying ^{15}N (month)	Year	Harvested crop	^{15}N removed with harvested crop		^{15}N remaining in crop residue		^{15}N measured in 90-cm soil profile	
			Disked	Nondisk	Disked	Nondisk	Disked	Nondisk
			kg ha^{-1}					
9 (June)	1989	Wheat	0.98	1.07	0.71	1.01	0.87	0.94
9 (June)	1990		1.40	1.34	0.48	0.56	0.70	0.70
Year			*†		**		*	
Tillage			NS		*		NS	
Year × Tillage			NS		NS		NS	
15 (Dec.)	1989	Cotton	0.30	0.24	0.28	0.23	1.08	1.21
15 (Dec.)	1990		0.18	0.16	0.27	0.26	0.76	0.60
Year			**		NS		**	
Tillage			*		NS		NS	
Year × Tillage			NS		NS		NS	
25 (Oct.)	1990	Corn	0.11	0.08	0.00	0.00	0.69	0.83
25 (Oct.)	1991		0.42	0.47	0.52	0.31	–‡	–
Year			***		***		–	
Tillage			NS		NS		NS	
Year × Tillage			NS		NS		–	
33 (June)	1991	Wheat	0.19	0.27	0.07	0.10	1.04	1.28
33 (June)	1992		0.22	0.14	0.06	0.05	–	–
Year			NS		*		–	
Tillage			NS		NS		NS	
Year × Tillage			**		NS		–	

† NS, *, **, and *** denote no statistical significance, or significance at the 0.1, 0.05, and 0.01 probability levels.
‡ ^{15}N measurements were not made on soil samples collected from Rotation II.

Table 8. Periodic accounting for the 4.2 kg ^{15}N ha^{-1} applied one time to cotton grown in a 2-yr, three-crop rotation on Norfolk loamy sand.

Months after applying ^{15}N (month)	Year	Harvested crop	^{15}N removed with harvested crop: Disked		Nondisk	^{15}N remaining in crop residue: Disked		Nondisk	^{15}N measured in 90-cm soil profile: Disked		Nondisk
			kg ha^{-1}								
	1989	Cotton	0.63		0.56	0.59		0.53	0.56		1.08
6 (Dec.)	1990		0.28		0.33	0.55		0.46	0.10		0.16
Year				*†			NS			***	
Tillage				NS			*			**	
Year × Tillage				**			NS			**	
16 (Oct.)	1990	Corn	0.08		0.11	0.00		0.00	0.48		0.72
16 (Oct.)	1991		0.39		0.38	0.47		0.35	–‡		–
Year				***			***			–	
Tillage				NS			NS			*	
Year × Tillage				NS			NS			–	
24 (June)	1991	Wheat	0.16		0.25	0.07		0.10	0.69		1.14
24 (June)	1992		0.20		0.08	0.04		0.03	–		–
Year				NS			***			–	
Tillage				NS			NS			NS	
Year × Tillage				***			**			–	

† NS, *, **, and *** denote no statistical significance, or significance at the 0.1, 0.05, and 0.01 probability levels.
‡ ^{15}N measurements were not made on soil samples collected from Rotation II.

or 24 mo, was 2.82, 1.88, and 0.87 kg ha^{-1}, respectively. These amounts accounted for 33.5, 32.5, or 20.5% of the fertilizer ^{15}N that had been applied to microplots initiated with corn, wheat, or cotton, respectively. Soil profile analyses when the final ^{15}N samples were collected accounted for 20.2, 19.8, and 21.7% of the applied fertilizer ^{15}N, respectively. The combined soil profile and crop removal analyses therefore accounted for 42 to 54% of the fertilizer ^{15}N.

Overall, the quantity of ^{15}N accounted for in this multi-year, multi-crop experiment is consistent with that reported for crops grown in monoculture and other rotations (Sanchez and Blackmer, 1988; Varvel and Peterson, 1990; Harris et al., 1994; Tobert and Reeves, 1994). The crop that received the ^{15}N fertilizer removed 11 to 21% of the labeled material in the harvested portion (i.e., corn grain, wheat grain, or seed cotton). This accounted for 52 to 63% of the total ^{15}N recovered in the 2-yr rotation. Changes in total N in the surface 15 cm also had a detectable effect on ^{15}N recovery. The differences were not statistically significant, but in disked and non-disked treatments, an average of 11 and 14% of the ^{15}N fertilizer was found in the 0- to 5-cm increment for the three sampling dates discussed in Table 5. For the 5 to 10 cm and 10 to 15 cm increments, the trend reversed itself with 4 and 3% or 2 and 1% of the applied fertilizer ^{15}N being accounted for in the disked and non-disked treatments, respectively.

A very important finding from this multi-year, multi-crop study was that most of the ^{15}N fertilizer loss appeared to occur during the initial cropping season when the fertilizer was applied. When total crop removal of ^{15}N, residual amounts of ^{15}N in current crop residues, and residual amounts of ^{15}N in the upper 90 cm of the soil profile are added and averaged across tillage treatment and year, approximately 48 to 56% of the ^{15}N applied to corn can be accounted for at all sampling dates. Similar calculations for ^{15}N applied to wheat or cotton account for 37 to 49% or 30 to 45% of the fertilizer ^{15}N. Lower recovery from cotton plots may have occurred because the fertilizer source was NH_4NO_3 and therefore 50% of the N was in the more mobile nitrate form rather than the 25% associated with the UAN solution applied to corn and wheat. Volatilization loss was not measured but may have been higher from wheat microplots than from the corn since the UAN was broadcast rather than banded. With respect to fertilizer management, the relatively rapid loss of approximately 50% of the fertilizer ^{15}N during the initial cropping season suggests that for economic and environmental efficiency for all three crops, consideration should be given to several N management options including applying the fertilizer in a series of split applications, injecting it beneath the soil surface, and/or using less mobile forms. Also, it is essential to account for all other sources of N since fertilizer is just one source upon which crops can draw.

Corn ear leaf, wheat foliage, and cotton petiole samples were also collected and analyzed for several of the crops grown after the labeled fertilizer was applied to the various microplots. These analyses consistently showed an enrichment in the ATM% ^{15}N compared with natural or background levels. The information (not presented) confirmed that ^{15}N was being accumulated throughout the growing season by all of the crops, but since the samples did not represent whole plant accumulation, the information gained did not justify the cost for isotopic analysis and would not be recommended for future studies.

SUMMARY AND CONCLUSIONS

Crop recovery and residual ^{15}N fertilizer in the upper 90 cm of a Norfolk loamy sand was measured within 48, 2.3- by 2.9-m microplots. Variation in seasonal rainfall caused significant differences in crop yield, ^{15}N fertilizer recovery and removal, and residual levels of ^{15}N in the soil profile. Surface tillage treatments caused few significant differences in ^{15}N fertilizer recovery. Approximately 22 to 35% of the ^{15}N applied one time to corn, wheat, or cotton crops was removed with the harvested portion of the fertilized crop or by a subsequent crop grown on the microplot as part of the three-crop, 2-yr rotation. An additional 20% of the applied fertilizer ^{15}N was accounted for in the upper 90 cm of the soil profile when measured 24 to 40 mo after application. Crop removal plus residual ^{15}N in crop residue and the soil profile accounted for 30 to 56% of the fertilizer ^{15}N. The remaining fertilizer ^{15}N was presumably lost through denitrification, volatilization, or leached below the 90-cm depth, most within the growing season during which the material was applied. This suggests that for optimum fertilizer efficiency and environmental sustainability, crop production practices on Coastal Plain soils should accommodate several N management options including applying the fertilizer in a series of split applications, injecting it beneath the soil surface, and/or using less mobile forms. Furthermore, it is essential to account for all other N sources since fertilizer is just one source which crops can draw upon.

REFERENCES

Bijeriego, M., R.D. Hauck, and R.A. Olson. 1979. Uptake, translocation and utilization of 15N-depleted fertilizer in irrigated corn. Soil Sci Soc. Am. J. 43:528–533.

Busscher, W.J., R.E. Sojka, and C.W. Doty. 1986. Residual effects of tillage on Coastal Plain soil strength. Soil Sci. 141:144–148.

Cheng, H.H., J.M. Bremner, and A.P. Edwards. 1964. Variations on nitrogen-15 abundance in soils. Science 146:1574–1575.

Dowdell, R.J., and C.P. Webster. 1980. A lysimeter study using nitrogen-15 on the uptake of fertilizer nitrogen by perennial ryegrass swards and losses by leaching. J. Soil Sci. 31:65–75.

Follett, R.F., L.K. Porter, and A.D. Halvorson. 1991. Border effects on nitrogen-15 fertilized winter wheat microplots grown in the Great Plains. Agron. J. 83:608–612.

Gilliam, J.W., and G.D. Hoyt. 1987. Effect of conservation tillage on fate and transport of nitrogen. p. 217–240. *In* T. J. Logan et al. (ed). Effects of conservation tillage on groundwater quality: Nitrates and pesticides. Lewis Publ., Chelsea, MI.

Harris, G.H., O.B. Hesterman, E.A. Paul, S.E. Peter, and R.R. Janke. 1994. Fate of legume and fertilizer nitrogen-15 in a long-term cropping systems experiment. Agron. J. 86:910–915.

Hauck, R.D., and J.M. Bremner. 1976. Use of tracer for soil and fertilizer nitrogen research. Adv. Agron. 28:219–266.

Hunt, P.G., D.L. Karlen, T.A. Matheny, and V.L. Quisenberry. 1996. Changes in carbon content of a Norfolk loamy sand after 14 years of conservation or conventional tillage. J. Soil Water Conserv. 51:255–258.

Jansson, S.L., and J. Persson. 1982. Mineralization and immobilization of soil nitrogen. p. 229–252. *In* F.J. Stevenson et al. (ed.) Nitrogen in agricultural soils. Agron. Monogr. 22. ASA and SSSA, Madison, WI.

Karlen, D.L., and D.T. Gooden. 1987. Tillage systems for wheat production in the southeastern Coastal Plains. Agron. J. 79:582–587.

Kitur, B.K., M.S. Smith, R.L. Blevins, and W.W. Frye. 1984. Fate of 15N depleted ammonium nitrate applied to no-tillage and conventional tillage corn. Agron J. 76:240–242.

Lee, J.A. 1984. Cotton as a world crop. *In* R.J. Kohel and C.F. Lewis (ed.) Cotton. Agron. Monogr. 24. ASA, CSSA, and SSSA, Madison, WI.

Meisinger, J.J., V.A. Bandel, G. Stanford, and J.O. Legg. 1985. Nitrogen utilization of corn under minimal tillage and moldboard plow tillage: 1. Four year results using labelled fertilizer on an Atlantic Coastal Plain soil. Agron. J. 77:602–611.

Olson, R.V. 1980. Fate of tagged nitrogen fertilizer applied to irrigated corn. Soil Sci. Soc. Am. J. 55:1616–1621.

Olson, R.V., L.S. Murphy, H.C. Moser, and C.W. Swallow. 1979. Fate of tagged fertilizer nitrogen applied to winter wheat. Soil Sci. Soc. Am. J. 43:973–975.

Reddy, G.B., and K.R. Reddy. 1993. Fate of nitrogen-15 enriched ammonium nitrated applied to corn. Soil Sci. Soc. Am. J. 57:111–115.

SAS Institute, Inc. 1985. SAS user's guide: Statistics, Ver. 5 Ed. Cary, NC.

Russelle, M.P., E.J. Deibert, R.D. Hauck, M. Stevanovic, and R.A. Olson. 1981. Effects of water and nitrogen management on yield and ^{15}N-depleted fertilizer use efficiency of irrigated corn. Soil Sci. Soc. Am. J. 45:553–558.

Sanchez, C.A., and A.M. Blackmer. 1988. Recovery of anhydrous ammonia-derived nitrogen 15 during three years of corn production in Iowa. Agron. J. 80:102–108.

Schepers, J.S., D.D. Francis, and M.T. Thompson. 1989. Simultaneous determination of total C, total N, and ^{15}N on soil and plant material. Commun. Soil Sci. Plant Anal. 20:949–959.

Shearer, G., and D.H. Kohl. 1993. Natural abundance of ^{15}N: Fractional contribution of two sources to a common sink and use of isotope discrimination. *In* R. Knowles and T.H. Blackburn (ed.) Nitrogen isotope techniques. Academic Press, Inc., New York.

Terman, G.L., and M.A. Brown. 1968. Crop recovery of applied fertilizer nitrogen. Plant Soil 29:48–65.

Timmons, D.R., and R.M. Cruse. 1990. Effect of fertilization method and tillage on nitrogen-15 recovery by corn. Agron. J. 82:777–784.

Torbert, H.A., R.L. Mulvaney, R.M. Vanden Heuvel, and R.G. Hoeft. 1992. Soil type and moisture regime effects on fertilizer efficiency calculation methods in a nitrogen-15 tracer study. Agron. J. 84:66–70.

Torbert, H.A., and D.W. Reeves. 1994. Fertilizer nitrogen requirements for cotton production as affected by tillage and traffic. Soil Sci. Soc. Am. J. 58:1416–1423.

Tyler, D.D., and G.W. Thomas. 1977. Lysimeter measurements of nitrate and chloride losses from soil under conventional and no-tillage corn. J. Environ. Qual. 6:63–66.

USDA-Soil Conservation Service (SCS). 1979. Soil survey of Florence and Sumter Counties, South Carolina. USDA-SCS in cooperation with the South Carolina Agr. Expt. Stn., Clemson, SC.

Varvel, G.E., and T.A. Peterson. 1994. Nitrogen fertilizer recovery by corn in monoculture and rotation systems. Agron. J. 82:935–938.

Walters, D.T., and G.L. Malzer. 1990. Nitrogen management and nitrification inhibitor effect on nitrogen-15 urea: I. Yield and fertilizer use efficiency. Soil Sci. Soc. Am. J. 54:115–122.

Westerman, R.L., and L.T. Kurtz. 1974. Isotopic and nonisotopic estimations of fertilizer nitrogen uptake by sudangrass in field experiments. Soil Sci. Soc. Am. Proc. 38:107–109.