Nitrogen Storage with Cover Crops and Nitrogen Fertilization in Tilled and Nontilled Soils

Upendra M. Sainju * and Bharat P. Singh

Cover Crops

ABSTRACT

Improved crop and N management practices are needed to increase soil N storage so that N fertilization rate and the potential for N leaching can be reduced in tilled and nontilled soils. We examined the influence of cover crops and N fertilization rates on N inputs from cover crops, cotton (*Gossypium hirsutum* L.) and sorghum [*Sorghum bicolor* (L.) Moench] and soil total N (STN) content at the 0- to 120-cm depth in no-tilled, strip-tilled, and chisel-tilled Dothan sandy loam (fine-loamy, kaolinitic, thermic, Plinthic Kandiudults) from 2000 to 2002 in central Georgia. Cover crops were legume [hairy vetch (*Vicia villosa* Roth)], nonlegume [rye (*Secale cereale* L.)], biculture of legume and nonlegume (vetch + rye), and winter weeds and N fertilization rates were 0, 60 to 65, and 120 to 130 kg N ha^{-1}. Nitrogen inputs in above- and belowground plant biomass varied with the season and were greater in vetch and vetch + rye with N rates than in rye and weeds with or without N in tilled and nontilled soils. The STN concentration varied with sampling times and decreased with depth. The STN content at 0 to 90 cm was greater in vetch and vetch + rye with N rates than in weeds with or without N in no-tilled and chisel-tilled soils. Similarly, STN content at 0 to 30 cm was greater with vetch and vetch + rye than with weeds in strip-tilled soil. As a result, N storage at 0 to 30 cm gained at 71 to 108 kg N ha^{-1} yr^{-1} in vetch and vetch + rye with N fertilization compared with a loss at 110 kg N ha^{-1} yr^{-1} to a gain at 40 kg N ha^{-1} yr^{-1} in weeds with or without N fertilization in no-tilled and chisel-tilled soils. In strip-tilled soil, N storage gained at 101 to 103 kg N ha^{-1} yr^{-1} with vetch and vetch + rye compared with a loss at 91 kg N ha^{-1} yr^{-1} with weeds. Nitrogen storage in tilled and nontilled soils can be increased by using legume or a biculture of legume and nonlegume cover crops compared with no cover crop with or without N fertilization. Because of similar levels of soil N storage and cotton and sorghum N uptake, legume can be replaced by biculture cover crop and N fertilization rate can be reduced to reduce the cost of N fertilization and the potential for N leaching.

Increase in the cost of N fertilization due to increase in the price of petroleum is a growing concern for sustainable crop production. Another concern is N leaching due to N fertilization to crops, resulting in reduced water quality. Therefore, improved soil and crop management practices are needed to increase N cycling and N storage so that the rate and cost of N fertilization and the potential for N leaching can be reduced.

Some of the practices to increase N storage and reduce the potential for N leaching without influencing crop yields are cover cropping and reduced rate of N fertilization in tilled and nontilled soils (McVay et al., 1989; Kuo et al., 1997; Sainju et al., 2000). Cover cropping provides additional residue that not only reduces soil erosion but also improves soil quality and productivity by increasing soil organic N (McVay et al., 1989; Kuo et al., 1997; Sainju et al., 2000). In humid subtropical regions, such as in the southeastern United States, cover crops are planted in the fall after summer crop harvest and grown during winter to provide vegetative cover. Winter cover crops use soil residual N that may otherwise leach into groundwater after crop harvest in the fall, and depending on the species, can fix atmospheric N, thereby supplying N for summer crops (Hargrove, 1986; Meisinger et al., 1990; Kuo et al., 1997). Although recommended rates of N fertilization are required following nonlegume cover crops, N fertilization rates can be either reduced or eliminated following legume cover crops to produce optimum crop yields (McVay et al., 1989; Sainju et al., 2000, Boquet et al., 2004) and reduce the potential for N leaching (Sainju et al., 1999; Bergstrom and Kirchmann, 2004). However, N fertilization can increase soil organic N by increasing crop biomass production and the amount of residue returned to the soil (Liang and Mackenzie, 1992; Gregorich et al., 1996; Omay et al., 1997).

While legume cover crops are effective in enriching soil inorganic N for increasing crop production, nonlegume cover crops are effective in increasing soil organic N through increased biomass production (Kuo et al., 1997; Sainju et al., 2000) compared with no cover crops. Nonlegume cover crops also reduce N leaching from the soil profile better than legume or no cover crops do (Meisinger et al., 1990; McCracken et al., 1994). Since neither legume nor nonlegume cover crops alone are effective enough to provide the combined benefits of supplying inorganic N, increasing N storage, and reducing N leaching, a biculture of legume and nonlegume cover crops would probably be more effective for these benefits compared with monoculture of legumes and nonlegumes.

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Abbreviations: STN, soil total N.

Cover cropping and N fertilization can have variable effects in storing N in tilled and nontilled soils due to differences in residue quantity and quality (residue C/N ratio) and variations in mineralization rates. Conventional tillage enhances mineralization of soil organic N by incorporating crop residue, disrupting soil aggregates, and increasing aeration, thereby reducing N storage (Dalal and Mayer, 1986; Balesdent et al., 1990; Cambardella and Elliott, 1993). In contrast, conservation tillage can increase N storage in the surface soil by minimizing soil disturbance (Jastrow, 1996; Allmaras et al., 2000; Sainju et al., 2002). Nitrogen storage below the 7.5-cm depth, however, can be higher in tilled soils, depending on the soil texture, due to residue incorporation at greater depths (Jastrow, 1996; Clapp et al., 2000). Soil N storage may be impacted by the interaction of tillage with cover cropping and N fertilization rate (Gregorich et al., 1996; Wanniarachchi et al., 1999; Sainju et al., 2002), soil texture and sampling depth (Ellert and Bettany, 1995), and time since treatments were initiated (Liang et al., 1998). Conservation tillage is getting more popular because of its positive or neutral influence on crop yields and improved soil productivity and water quality compared with conventional tillage. Conservation tillage can not only result in higher returns due to overall reductions in input costs, but also reduces soil erosion and compaction, limits movement of nutrients and pesticides, and increases soil organic matter and water content due to greater accumulation of crop residue at the soil surface than conventional tillage (Sandretto, 2001).

Although information is available about the effects of cover crops and N fertilization on soil organic N, little is known about the influence of legume and nonlegume bicultural cover crops compared with monoculture cover crops and N fertilization rates on crop residue N input and N storage in tilled and nontilled soils. Besides N fertilization, N can be recycled and/or added not only from aboveground but also from belowground biomass. Aboveground biomass, such as grains and lint, is harvested for food and fiber, and stems and leaves (or straws, stalks) for animal feed (hay), litter, or fuel. As a result, belowground biomass, such as roots, forms the main source of plant N input. We hypothesized that cover cropping and N fertilization would increase soil total N (STN) content in tilled and nontilled soils due to greater amounts of residue N returned to the soil than no cover cropping and N fertilization and that a mixture of legume and nonlegume cover crops would be more effective in increasing STN than either species alone. Our objectives were to: (i) examine the amount of residue N supplied by above- and belowground biomass of cover crops, cotton, and sorghum as influenced by cover crops and N fertilization rates in tilled and nontilled soils from 2000 to 2002, and (ii) determine the influence of cover crops and N fertilization rates on STN storage at the 0- to 120-cm depth in tilled and nontilled soils in the warm, humid region of the southeastern United States.

MATERIALS AND METHODS

Experimental Site and Treatments

The experiment was conducted in no-tilled, strip-tilled, and chisel-tilled Dothan sandy loam in the same area from 1999 to 2002 at the Agricultural Research Station farm, Fort Valley State University, Fort Valley, GA (32°6' N, 83°9' W). The areas with different tillage practices were established in 1995, before which these were tilled with disc harrow and chisel plow to a depth of 20 cm. In strip-tilled plots, cropping rows were subsoiled to a depth of 35 cm in a narrow strip of 30 cm width, thereby leaving 60 cm areas between rows undisturbed. The surface-tilled zone was leveled by crow-foot packer behind the subsoiler. Chisel-tilled plots continued to be tilled with disc harrow and chisel plow. No-tilled plots were left undisturbed, except for planting cover crops, cotton, and sorghum. Soils in tilled and nontilled plots had pH of 6.5 to 6.7 and sand content of 650 g kg^{-1}, silt 250 g kg^{-1}, and clay 100 g kg^{-1} soil at the 0- to 30-cm depth. The clay content increased to 350 g kg^{-1} below 30 cm. Because of different tillage practices, STN content at 0 to 15 cm before the initiation of the experiment in October 1999 was 1657 kg N ha^{-1} in no-tilled, 1693 kg N ha^{-1} in strip-tilled, and 1508 kg N ha^{-1} in chisel-tilled plots. At 15 to 30 cm, STN was 1155 kg N ha^{-1} in no-tilled, 1038 kg N ha^{-1} in strip-tilled, and 1155 kg N ha^{-1} in chisel-tilled plots. Previous crops from 1995 to 1999 were tomato (*Lycopersicum esculentum* Mill) and silage corn (*Zea mays* L.). Temperature and rainfall data were collected from a weather station, 20 m from the experimental site.

Treatments in tilled and nontilled plots included four cover crops {legume [hairy vetch (V*icia villosa* Roth)], nonlegume [rye (*Secale cereale* L)], legume and nonlegume (hairy vetch + rye) biculture, and winter weeds}, and three N fertilization rates (0, 60–65, and 120–130 kg N ha^{-1}). The 120 kg N ha^{-1} is the recommended rate of N fertilization for cotton with a lint yield goal of 1700 kg ha^{-1} in central Georgia (University of Georgia, 1999). Similarly, 130 kg N ha^{-1} is the recommended rate of N fertilization for sorghum with a grain yield goal of 5200 kg ha^{-1} (University of Georgia, 2001). A randomized complete block design with a split plot arrangement was used, with cover crop as the main plot factor and N fertilization rate as the split-plot factor in no-tilled, strip-tilled, chisel-tilled soils. Each experimental unit had three replications. The split plot size of an experimental unit was 7.2 by 7.2 m.

Cover Crop Management

Cover crops were planted in October–November of each year from 1999 to 2001 in the same plot to examine their long-term influence on STN. Hairy vetch seeds were drilled at 28 kg ha^{-1} after inoculating with *Rhizobium leguminosarum* (bv. viceae) and rye at 80 kg ha^{-1} using a row spacing of 15 cm. In the hairy vetch + rye biculture, hairy vetch was drilled at 19 kg ha^{-1} (68% of monoculture), followed by rye at 40 kg ha^{-1} (50% of monoculture) in between vetch rows. The rates of hairy vetch and rye in the biculture were based on the recommendation of Clark et al. (1994). Cover crops were drilled in plots without tillage because previous studies have shown that cover crop aboveground biomass yields and N accumulation were not significantly influenced by tillage practices (Sainju et al., 2002). No fertilizers, herbicides, or insecticides were applied to cover crops.

In April of each year from 2000 to 2002, cover crop biomass yield was determined by hand harvesting plant samples from two 1 m^2 areas randomly within each experimental unit and weighed in the field. After mixing the samples thoroughly, a subsample (approximately 100 g) was collected for determinations of dry matter yield and N concentration and the remain-

der of the plant samples were returned to the harvested area and spread uniformly by hand. In the winter weed treatment, weeds, dominated by henbit (*Lamium amplexicaule* L.) and cut-leaf evening primrose (*Oenolthera laciniate* Hill), were collected using the same procedure. Plant samples were oven-dried at 60°C for 3 d, weighed, and ground to pass a 1-mm screen. After sampling, cover crops and weeds were mowed with a rotary mower to prevent residues from dragging during tillage and seeding. In no-tilled and strip-tilled plots, cover crops and weeds were killed by spraying 3.36 kg a.i. ha^{-1} of glyphosate [N-(phosphonomethyl) glycine]. In chisel-tilled plots, cover crops and weeds were killed by disc harrowing and chisel plowing. Residues were allowed to decompose for 2 wk before cotton and sorghum planting.

Cotton and Sorghum Management

At cotton and sorghum planting in May of each year from 2000 to 2002, P {as triple superphosphate [$Ca(H_2PO_4)_2$]} fertilizer was broadcast at 36 kg ha^{-1} for cotton and 40 kg ha^{-1} for sorghum and K [as muriate of potash (KCl)] fertilizer was broadcast at 75 kg ha^{-1} for cotton and 80 kg ha^{-1} for sorghum in all plots based on soil test and crop requirement. At the same time, B [from boric acid (H_3BO_3)] fertilizer was also broadcast at 0.23 kg ha^{-1} for cotton. Nitrogen fertilizer [as ammonium nitrate (NH_4NO_3)] was applied at three rates (0, 60, 120 kg N ha^{-1}) for cotton in 2000 and 2002, half of which was broadcast at planting and the other half broadcast 6 wk later. Similarly, NH_4NO_3 was applied at three rates (0, 65, 130 kg N ha^{-1}) for sorghum in 2001, two-thirds of which was broadcast at planting and the other one-third broadcast 6 wk later. The fertilizers were left at the soil surface in no-tilled, partly incorporated into the soil in strip-tilled, and completely incorporated in chisel-tilled plots during tillage. While no-tilled plots were left undisturbed, strip-tilled plots were tilled in rows (0.9 m apart), and chisel-tilled plots were harrowed using a disc harrow, followed by chiseling and leveling with a S-tine harrow.

Following tillage, glyphosate-resistant cotton [cv. DP458BR (Delta Pine Land Co., Hartsville, SC)] at 8 kg ha^{-1} in 2000 and 2002 and sorghum [cv. 9212Y (Pioneer Hi-Bred Int., Huntsville, AL)] at 12 kg ha^{-1} in 2001 were planted in eight-row (each 7.2 m long) plots (0.9 m spacing) with a no-till equipped unit planter. Although the experiment was planned to plant continuous cotton from 2000 to 2002, sorghum was planted in 2001 to reduce the incidence of diseases and pests. Appropriate herbicides, pesticides, and growth regulators were applied in cotton and sorghum during their growth to control weeds, pests, and vegetative growth. Irrigation (totaling 75–100 mm every year using reel rain gun) was applied immediately after planting and fertilization and during dry periods in tilled and nontilled plots to prevent moisture stress.

In October to November of each year from 2000 and 2002, aboveground cotton biomass samples containing stems, leaves, and lint (including seeds) were hand harvested from two 3.24 m^2 areas a week before the determination of lint yield. After removing lint and seeds, biomass samples containing stems and leaves were weighed, chopped to 2.5 cm length, and mixed thoroughly, from which a representative subsample of 100 g was collected, oven-dried at 60°C for 3 d, and ground to 1 mm for N analysis. Lint yield was determined by hand harvesting lint containing seeds from two central rows (6.2 by 1.8 m), separating lint from seeds after ginning, and weighing them separately. Similarly, in November 2001, aboveground sorghum biomass containing stems and leaves (after removing grains) were collected from two 3.24 m^2 areas randomly in places next to yield rows within the plot, a week before the determination of grain yield. These were weighed, chopped to 2.5 cm length, and mixed thoroughly, from which a subsample of 100 g was oven-dried and ground to 1 mm for N analysis. Grain yield was determined by hand harvesting heads from two central rows (6.2 by 1.8 m), separating grains from heads, and weighing. After collecting samples, cotton lint containing seeds and sorghum grain were removed from the remaining plants within the plot from 2000 to 2002 using a combine harvester, and biomass residues containing stems and leaves were returned to the soil.

Soil and Root Sample Collection and Analysis

Within 2 wk after returning cover crop, cotton, and sorghum residues to the soil, soil and root biomass samples were collected from the 0- to 120-cm depth from each plot using a hydraulic probe (5 cm i.d.) with a plastic liner inside, both of which were attached to a tractor. In each plot, soil cores were sampled from four locations, two in rows and two between the rows. Samples were stored at 4°C until roots were separated from the soil. Samples were collected in April and November of each year from 2000 to 2002 for root biomass of cover crops, cotton, and sorghum and soils under them. For analyzing STN, liners containing soil and root samples were cut into 0 to 15, 15 to 30, 30 to 60, 60 to 90, and 90 to 120 cm segments from the end containing topsoil to represent respective soil depths and 50 g of root-free soil samples were collected from each segment. Soil samples from four locations within a plot were composited by depth, air-dried, and ground to 2 mm. The remaining samples were stored at 4°C until roots were separated from the soil. Bulk density of soil at each depth and sampling time was determined by the diameter of the probe, thickness of the soil layer, and mass of the oven-dried soil. The mass of the oven-dried soil was determined by drying 10 g of field-moist soil subsample at 105°C for 24 h and then correcting for the moisture content.

Soil samples collected for determining root biomass were washed thoroughly with water in a nest of sieves containing 1.00-mm sieve at the top and 0.5-mm sieve at the bottom. About 500 g soil was washed at a time with a fine spray of water on the top and bottom sieves and roots retained on both sieves were picked by tweezers and collected in plastic bags. As a result, all of the coarse and most of fine roots were collected. The process was repeated several times until all soils from the 0- to 120-cm depth from a plot were washed and roots separated. Roots from four cores within a plot were composited by depth, oven-dried at 60°C for 3 d, weighed, ground, and passed through a 1-mm sieve for N determination.

Total N concentration (g N kg^{-1} plant dry weight) in aboveground (stems + leaves) and belowground (roots) biomass of cover crops, cotton, and sorghum was determined by using the dry combustion C and N analyzer (LECO Co., St. Joseph, MI). Similarly, STN concentration (g N kg^{-1} soil) in soil samples was determined by the C and N analyzer. Nitrogen content (kg N ha^{-1}) in cover crop, cotton, and sorghum biomass was determined by multiplying dry matter weight by total

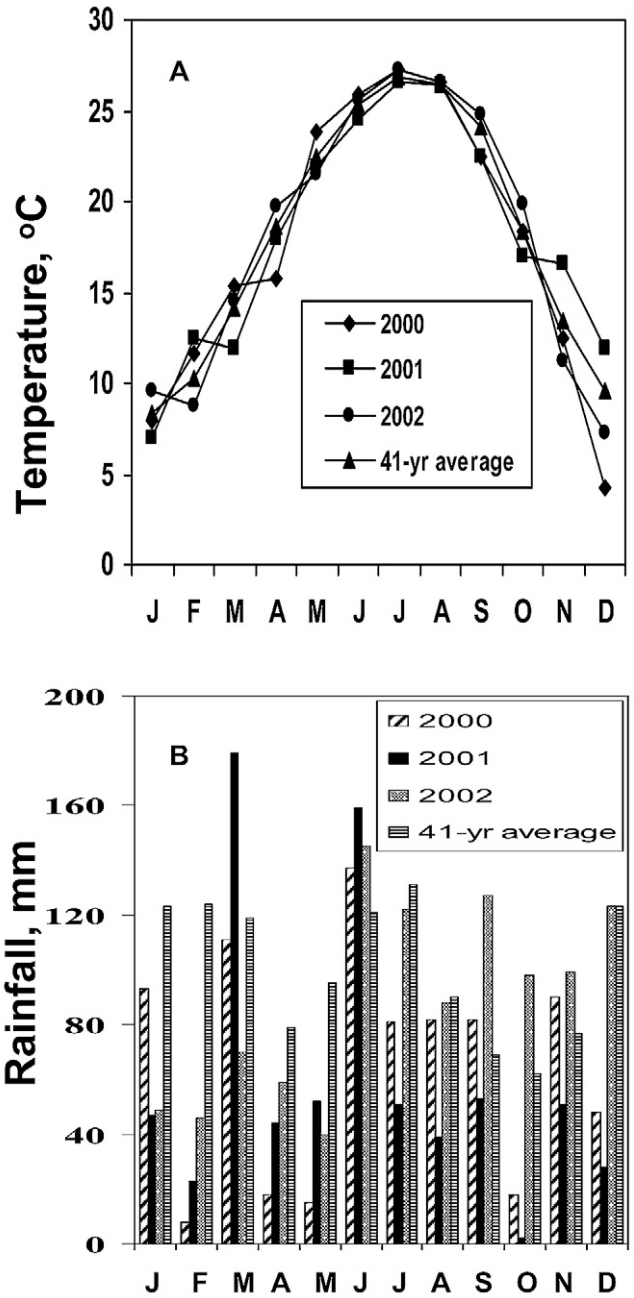

Fig. 1. (A) Average monthly air temperature and (B) total monthly rainfall from January 2000 to December 2002 and the 41-yr average near the study site in central Georgia.

N concentration. Similarly, STN content (kg N ha^{-1}) in soil at a particular depth was determined by multiplying STN concentration by bulk density (for that depth) and soil depth. Bulk density ranged from 1.35 Mg m^{-3} at 30 to 60 cm in chisel-tilled soil to 1.60 Mg m^{-3} at 60 to 90 cm in no-tilled soil.

Data Analysis

Data for N content in above- and belowground biomass of cover crops, cotton, and sorghum at each sampling time in no-tilled, strip-tilled, and chisel-tilled soils were analyzed using the split-plot analysis in the MIXED procedure of SAS after testing for homogeneity of variance (Littell et al., 1996). Cover crop was considered as the main plot and N fertilization rate as the split-plot treatment. As a result, cover crop, N rate, and cover crop × N rate interaction in each tillage practice and sampling time were considered as fixed effects, and replication and cover crop × replication interaction were considered as random effects. For STN in each tillage practice, data were similarly analyzed using the Analysis of Repeated Measure in the MIXED procedure of SAS. Cover crop was considered as the main plot, N rate as the split-plot, and soil depth and sampling time as the repeated measure treatments for analysis. As a result, cover crop, N rate, soil depth, sampling time, and their interactions were considered as fixed effects, and replication and cover crop × replication interaction were considered as random effects. Means were separated by using the least square means test when treatments and their interactions were significant. Statistical significance was evaluated at $P \leq 0.05$, unless otherwise stated.

RESULTS AND DISCUSSION

Crop Residue Nitrogen

Differences in N contents in above- and belowground biomass residues of cover crops, cotton, and sorghum from 2000 to 2002 resulted in a significant cover crop × N fertilization interaction in each tillage practice and sampling time. While N content in aboveground biomass was higher in cover crops than in winter weeds, it was higher in hairy vetch than in rye with or without N fertilization in tilled and nontilled soils (Table 1). Similarly, N content in vetch + rye biculture was either similar to vetch or between vetch and rye monocultures. Overall, N content in vetch and vetch + rye with N fertilization was greater than in rye and weeds with or without N fertilization in tilled and nontilled soils in each sampling time. While N content in rye decreased from 2000 to 2002 possibly due to a reduction in soil available N (Sainju et al., 2007), N content in vetch and vetch + rye was lower in 2001 than in 2000 and 2002 because of lower growing season rainfall (October 2000–April 2001) (Fig. 1B) and a cold temperature in December 2000 (Fig. 1A) that reduced growth and production of vetch. Except in certain cases, N content in cover crop belowground biomass amounted to <15% of that of the aboveground biomass. Since N fertilization was applied to cotton and sorghum and not to cover crops, N in rye and weed biomass contained recycled residual soil N while N in vetch and vetch + rye biomass contained both residual soil N and N fixed from the atmosphere.

Because of increased N supply, N content in aboveground cotton and sorghum residues also increased following vetch and vetch + rye compared with following rye and weeds in tilled and nontilled soils (Table 1). Cotton and sorghum N increased with increased N fertilization rate following rye but was not influenced by N fertilization following vetch and vetch + rye. At 120 to 130 kg N ha^{-1}, N content in cotton and sorghum residue following rye was comparable with that following vetch and vetch + rye. This shows that at low or no N rate, rye reduced N uptake by cotton and sorghum possibly due to N immobilization in the soil, but at high N rate the effect of rye was negligible. In contrast, vetch had similar effect in N uptake by cotton and sorghum at all N rates. Similar results were obtained with vetch + rye with or without N fertilization. Boquet et al. (2004) reported that cotton N uptake increased with increasing N fertilization rates from 0 to 118 kg N ha^{-1} with wheat cover crop or native cover but decreased with hairy vetch. Similar results of increased sorghum N uptake with increasing N fertilization rate with rye but not with vetch were

Table 1. Effects of cover crops and N fertilization rates on above- and belowground biomass residue N of cover crops, cotton, and sorghum returned to the soil from 2000 to 2002 in no-tilled, strip-tilled, and chisel-tilled soils.

		2000§				2001§				2002§				
		April		November		April		November		April		November		
N rate†	Cover crop‡	A¶	B¶	A	B	A	B	A	B	A	B	A	B	Total
kg N ha^{-1}		kg residue N ha^{-1}												
		No-tilled soil												
0	weeds	16	1	82	3	16	5	53	3	40	2	31	3	255
	rye	68	2	114	6	35	8	39	6	20	5	48	4	355
	vetch	211	1	266	1	50	8	100	3	167	4	118	3	932
	vetch + rye	135	9	176	7	56	9	58	6	246	4	89	3	798
60–65	weeds	26	1	121	6	11	7	46	4	9	2	47	4	284
	rye	88	1	191	4	31	6	48	6	23	4	59	7	468
	vetch	183	1	243	4	70	9	158	4	106	8	80	5	872
	vetch + rye	104	10	182	6	73	5	79	5	159	5	89	4	721
120–130	weeds	21	1	143	2	11	6	130	3	21	3	64	5	410
	rye	54	1	243	1	37	11	61	6	22	3	54	6	499
	vetch	173	6	345	3	61	7	163	3	100	7	75	3	773
	vetch + rye	54	9	260	1	81	8	86	4	92	5	88	4	692
LSD (0.05)		62	3	152	3	31	4	75	3	97	6	49	3	423
		Strip-tilled soil												
0	weeds	31	6	121	5	14	5	152	5	19	2	73	5	438
	rye	96	1	134	1	28	4	57	3	25	4	91	3	447
	vetch	120	4	176	6	72	18	158	4	150	3	98	4	813
	vetch + rye	97	19	203	3	65	14	139	5	110	4	88	4	751
60–65	weeds	35	1	185	3	26	3	187	3	33	1	90	7	574
	rye	37	1	152	1	28	5	111	3	37	2	102	4	483
	vetch	132	4	353	2	87	13	155	4	153	4	79	6	992
	vetch + rye	99	5	257	5	95	8	205	4	211	6	141	7	1043
120–130	weeds	40	1	168	6	15	3	193	4	35	2	109	6	582
	rye	65	1	266	1	31	5	135	2	29	5	130	4	674
	vetch	156	6	450	10	69	15	174	5	149	4	113	7	1158
	vetch + rye	81	16	299	5	98	7	184	4	149	4	107	4	958
LSD (0.05)		59	7	185	6	25	8	117	2	58	4	68	3	442
		Chisel-tilled soil												
0	weeds	14	1	135	1	10	5	124	3	14	2	103	5	417
	rye	46	2	83	7	25	6	61	4	23	4	37	6	304
	vetch	189	1	214	2	90	8	173	4	168	2	110	4	965
	vetch+rye	127	2	133	3	74	15	182	5	184	3	68	6	802
60–65	weeds	16	1	116	4	15	5	114	3	18	1	69	5	367
	rye	53	3	142	10	27	8	97	4	18	2	58	4	426
	vetch	144	1	230	8	78	6	261	3	128	2	85	4	950
	vetch + rye	130	1	247	4	77	10	159	6	229	3	138	4	1008
120–130	weeds	16	2	192	2	13	5	195	5	17	2	81	3	533
	rye	62	1	78	4	47	9	116	3	23	2	116	4	465
	vetch	183	1	167	3	110	11	234	3	118	4	125	4	963
	vetch + rye	85	1	227	2	79	18	146	6	199	3	104	5	875
LSD (0.05)		56	1	133	5	34	9	89	3	111	2	59	3	405

† N fertilization rates are 0, 60, and 120 kg N ha^{-1} for cotton in 2000 and 2002, and 0, 65, and 130 kg N ha^{-1} for sorghum in 2001.

‡ Cover crops are rye, cereal rye; vetch, hairy vetch; vetch + rye, hairy vetch and rye biculture; and weeds, winter weeds.

§ Nitrogen from cover crop residues were returned to the soil in April 2000, 2001, and 2002, from cotton residue in November 2000 and 2002, and from sorghum residue in November 2001.

¶ A = aboveground biomass N, and B = belowground biomass N.

reported by several researchers (Hargrove, 1986; McVay et al., 1989). Cotton and sorghum residue N were not significantly different between vetch and vetch + rye treatments, suggesting that vetch can be replaced by vetch + rye for optimum crop N uptake. Another reason for replacing vetch by vetch + rye is the greater soil NO_3–N accumulation at the 0- to 120-cm depth with vetch than with vetch + rye (Sainju et al., 2007). Excessive accumulation of NO_3–N in the soil profile increases the potential for N leaching (Hahne et al., 1977; Timmons and Dylla, 1981), although N leaching depends on soil properties, climatic conditions, and management practices (Jokella and Randall, 1989; Pang et al., 1998). Since rye reduces N leaching by 29 to 94% compared with –6 to 48% with hairy vetch (Meisinger et al., 1990; McCracken et al., 1994), replacement of vetch by vetch + rye could reduce the potential for N leaching. While cover crop N content was similar between tilled and nontilled soils, N content in 2001 sorghum and 2002 cotton residues was higher in strip-tilled and chisel-tilled soils than in no-tilled soil. As with cover crops, N content in belowground biomass

Table 2. Analysis of variance for total N content in no-tilled, strip-tilled, and chisel-tilled soils.

Source	No-tilled soil	Strip-tilled soil	Chisel-tilled soil
		P > *F*	
Cover crop (C)	0.182	0.150	0.851
N fertilization (F)	0.884	0.544	0.551
C × F	0.544	0.364	0.750
Soil depth (D)	<0.001	<0.001	<0.001
C × D	0.037	0.006	<0.001
F × D	0.429	0.898	0.004
C × F × D	0.035	0.543	<0.001
Sampling time (T)	0.038	0.043	0.042
C × T	0.260	0.414	0.831
F × T	0.985	0.994	0.579
C × F × T	0.785	0.718	0.900
D × T	0.506	0.566	0.200
C × D × T	0.969	0.951	0.881
F × D × T	0.905	0.897	0.873
C × F × D × T	0.842	0.959	0.854

of cotton and sorghum was <8% of that in aboveground biomass. The lower N content in belowground biomass of cover crops, cotton, and sorghum was due to lower biomass yield (43–333 kg ha^{-1}) and N concentration (11–20 g N kg^{-1}) than aboveground biomass yield (7.4–14.3 Mg ha^{-1}) and N concentration (15–33 g kg^{-1}). These values are similar to those reported in the literature (McVay et al., 1989; Boquet et al., 2004).

Total cover crop, cotton, and sorghum residue N in above- and belowground biomass returned to the soil from 2000 to 2002 was greater in vetch with 0 kg N ha^{-1} than in rye and weeds with or without N fertilization in no-tilled soil (Table 1). In strip-tilled soil, total residue N was greater in vetch with 120 to 130 kg N ha^{-1} or vetch + rye with 60 to 65 kg N ha^{-1} than in rye and weeds with or without fertilizer N. In chisel-tilled soils, total residue N was greater in vetch with or without N fertilization or vetch + rye with 60 to 65 kg N ha^{-1} than in rye and weeds with or without N fertilization. It is clear that higher amount of N supplied by vetch and vetch + rye than by rye and weeds also increased N contents in cotton and sorghum residues, thereby increasing total crop residue N returned to the soil with these treatments in tilled and nontilled soils, regardless of N fertilization rates.

Soil Total Nitrogen

The STN content was significantly influenced by soil depth and sampling time in tilled and nontilled soils (Table 2). Interactions were significant for cover crop × soil depth in no-tilled, strip-tilled, and chisel-tilled soils, N fertilization × soil depth in chisel-tilled soil, and cover crop × N fertilization × soil depth in no-tilled and chisel-tilled soils.

Since STN content can not be averaged across soil depths, STN concentration was used to measure the effects of treatments on N distribution across depths and sampling times. A significant interaction between soil depth and sampling time was observed for STN concentration in tilled and nontilled soils. The STN concentration decreased with depth in tilled and nontilled soils (Fig. 2). Except at 15 to 30 cm and 60 to 90 cm in no-tilled soil, STN concentration was usually greater in November 2002 than in other sampling times in no-tilled, strip-tilled, and chisel-tilled soils (Fig. 2A, 2B, and 2C).

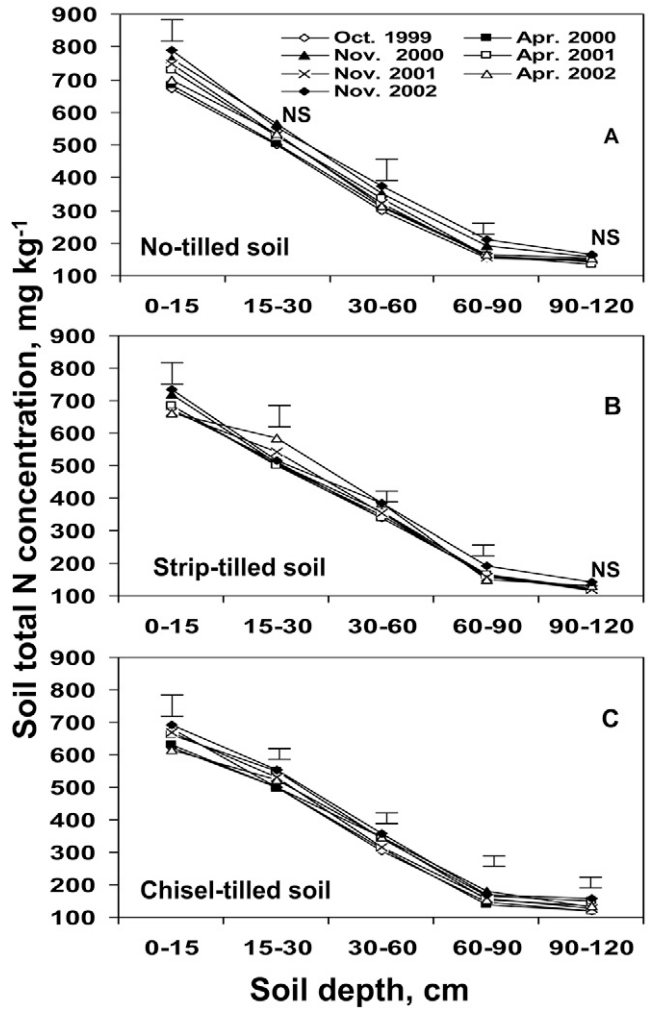

Fig. 2. Soil total N concentration at the 0- to 120-cm depth from October 1999 to November 2002 in (A) no-tilled, (B) strip-tilled, and (C) chisel-tilled soils averaged across cover crops and N fertilization rates. Vertical lines above the points represent least significant difference at *P* = 0.05 between time of sampling at a particular depth. NS = not significant.

The increased STN concentration in November 2002 compared with other sampling times could be a result of continuous N addition from cover crop, cotton, and sorghum residues and from N fertilizer from 2000 to 2002, since the experiment was continued in the same place during these years. Cover crop N was lower in April 2001 than in April 2000 but was similar to or higher in April 2002 than in April 2000 (Table 1). It is possible that increased cover crop N addition in April 2002, together with increased soil residual N accumulation resulting from previous cropping and N fertilization, could have increased STN concentration in November 2002 in tilled and nontilled soils. It is not surprising to observe decreased STN concentration with depth because organic matter concentration also decreases with depth.

In no-tilled soil, STN content at 0 to 15 cm, averaged across sampling times, was greater in vetch with 60 to 65 kg N ha^{-1} and vetch + rye with 60 to 130 kg N ha^{-1} than in weeds with 0 kg N ha^{-1} (Table 3). At 15 to 60 cm, STN was greater in vetch with 120 to 130 kg N ha^{-1} than in weeds with 120 to 130 kg N ha^{-1}. Similarly at 60 to 90 cm, STN was greater in vetch + rye with 60 to 65 kg N ha^{-1} than in weeds and rye with or without N fertilization. In

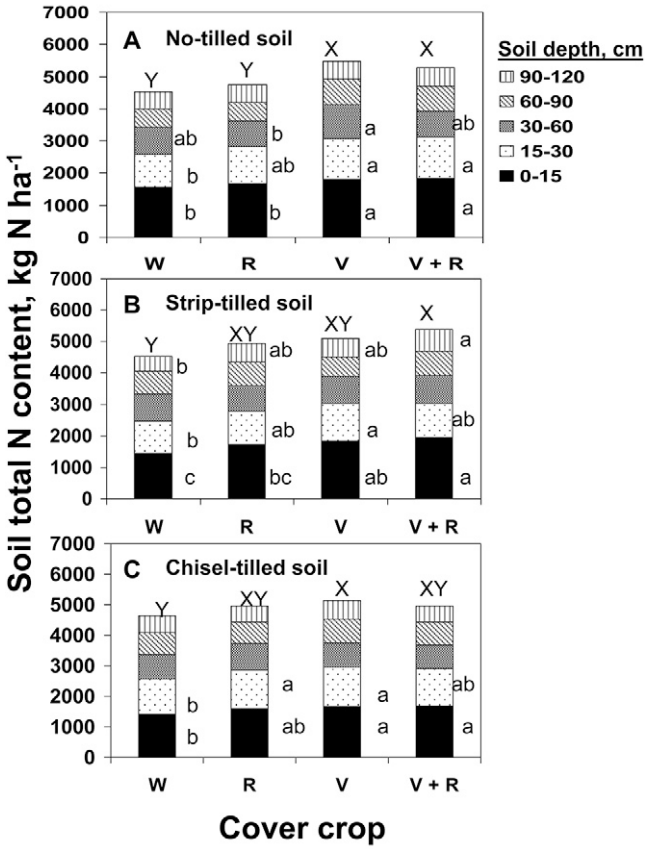

Fig. 3. Soil total N content at the 0- to 120-cm depth in (A) no-tilled, (B) strip-tilled, and (C) chisel-tilled soils averaged across N fertilization rates and sampling times as influenced by cover crops. Cover crops are W, winter weeds; R, rye; V, hairy vetch, and V + R, hairy vetch + rye. Bars followed by the same lowercase letters at the right within a soil depth are not significantly different at *P* ≤ 0.05 by the least square means test. Bars followed by the same uppercase letters at the top at the 0- to 120-cm soil depth are not significantly different at *P* ≤ 0.05 by the least square means test.

Table 3. Effects of cover crops and N fertilization rates on total N content at the 0- to 120-cm depth in no-tilled and chisel tilled soils averaged across sampling times.

N rates†	Cover crop‡	Soil total N content at various depths, cm 0–15	15–30	30–60	60–90	90–120
kg N ha^{-1}		kg N ha^{-1}				
		No-tilled soil				
0	weeds	1424	1058	829	595	560
	rye	1647	1151	788	578	680
	vetch	1722	1258	1023	853	664
	vetch + rye	1815	1265	808	655	589
60 to 65	weeds	1658	1011	871	569	579
	rye	1801	1092	892	624	528
	vetch	1884	1215	1091	743	576
	vetch + rye	1854	1255	939	869	719
120 to 130	weeds	1592	1018	836	532	481
	rye	1558	1236	693	530	473
	vetch	1837	1298	1092	730	471
	vetch + rye	1856	1277	737	754	469
LSD (0.05)		393	274	238	201	—-
		Chisel-tilled soil				
0	weeds	1316	1127	830	603	536
	rye	1472	1324	880	668	428
	vetch	1613	1292	810	640	601
	vetch + rye	1621	1256	716	596	456
60 to 65	weeds	1550	1234	701	630	583
	rye	1650	1227	823	684	573
	vetch	1703	1278	879	827	641
	vetch + rye	1710	1253	859	873	585
120 to 130	weeds	1341	1127	835	651	548
	rye	1659	1278	836	813	575
	vetch	1677	1289	738	818	589
	vetch + rye	1685	1218	710	778	531
LSD (0.05)		274	194	—	192	—

† N fertilization rates are 0, 60, and 120 kg N ha^{-1} for cotton in 2000 and 2002, and 0, 65, and 130 kg N ha^{-1} for sorghum in 2001.

‡ Cover crops are rye, cereal rye; vetch, hairy vetch; vetch + rye, hairy vetch and rye biculture; and weeds, winter weeds.

chisel-tilled soil, STN at 0 to 15 cm was greater in vetch + rye with 60 to 65 kg N ha^{-1} than in weeds with 0 and 120 to 130 kg N ha^{-1}. At 15 to 30 cm, STN was greater in rye with 0 kg N ha^{-1} than in weeds with 0 and 120 to 130 kg N ha^{-1}. At 60 to 90 cm, STN was greater in vetch + rye with 60 to 65 kg N ha^{-1} than in cover crops with 0 kg N ha^{-1} and in weeds with 60 to 130 kg N ha^{-1}.

Averaged across N fertilization rates and sampling times, STN at 0 to 15 and 0 to 120 cm was greater with vetch and vetch + rye than with rye and weeds in no-tilled soil (Fig. 3A). At 15 to 30 cm, STN was greater with vetch and vetch + rye than with weeds. Similarly, at 30 to 60 cm, STN was greater with vetch than with rye. In strip-tilled soil, STN at 0 to 15, 90 to 120, and 0 to 120 cm was greater with vetch + rye than with weeds (Fig. 3B). At 15 to 30 cm, STN was greater with vetch than with weeds. In chisel-tilled soil, STN at 0 to 15 cm was greater with vetch and vetch + rye than in weeds (Fig. 3C). At 15 to 30 cm, STN was greater with vetch and rye than with weeds. At 0 to 120 cm, STN was greater with vetch than with weeds. Averaged across cover crops and sampling times, STN at 0 to 15 cm was greater with 60 to 65 than with 0 kg N ha^{-1} in chisel-tilled soil (Fig. 4).

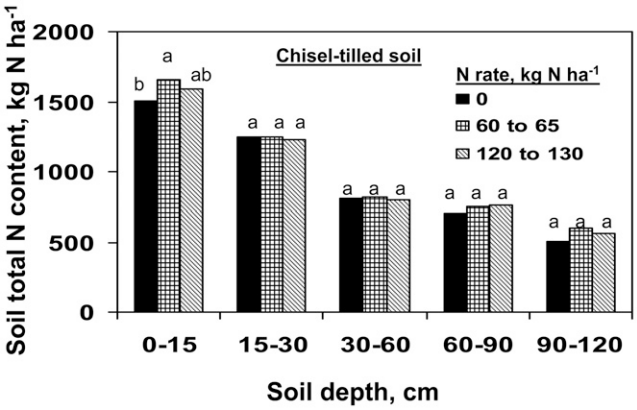

Fig. 4. Soil total N content at the 0- to 120-cm depth in chisel-tilled soil averaged across cover crops and sampling times as influenced by N fertilization rates. Bars followed by the same letter at the top are not significantly different at *P* ≤ 0.05 by the least square means test.

The greater STN content in vetch and vetch + rye with N fertilization than in rye and weeds with or without N fertilization in no-tilled and chisel-tilled soils (Table 3) or greater with vetch and vetch + rye than with rye and weeds in all tillage practices (Fig. 3) was due to greater N inputs from cover crop, sorghum, and cotton residues with these treatments (Table 1) and from N fertilization. Total crop residue N returned to the soil was two to three times greater with vetch and vetch + rye than with rye and weeds in tilled and nontilled soils, regardless of N fertilization rates. Continuous application of greater

Table 4. Net gain or loss in total N content in no-tilled and chisel-tilled soils from October 1999 to November 2002 as influenced by cover crops and N fertilization.

		Net soil total N content† at various depths, cm					
		No-tilled soil			Chisel-tilled soil		
N rate‡	Cover crop§	0–15	15–30	0–30	0–15	15–30	0–30
		kg N ha^{-1}					
0	weeds	–233	–97	–330	–192	–18	–210
	rye	–10	–4	–14	–36	169	133
	vetch	65	193	258	105	137	242
	vetch + rye	158	110	268	113	101	214
60 to 65	weeds	1	–144	–143	42	79	121
	rye	144	–63	81	142	72	214
	vetch	227	60	287	195	120	315
	vetch + rye	197	100	297	202	98	300
120 to 130	weeds	–65	–137	–202	–167	–18	–185
	rye	–99	81	–18	151	123	274
	vetch	180	143	323	169	134	303
	vetch + rye	199	122	321	177	63	240
LSD (0.05)		54	35	75	58	40	80

† Net soil total N content = Average soil total N content for a treatment from April 2000 to November 2002 – soil total N content in October 1999.

‡ N fertilization rates are 0, 60, and 120 kg N ha^{-1} for cotton in 2000 and 2002, and 0, 65, and 130 kg N ha^{-1} for sorghum in 2001.

§ Cover crops are rye, cereal rye; vetch, hairy vetch; vetch + rye, hairy vetch and rye biculture; and weeds, winter weeds.

Table 5. Net gain or loss in total N content in strip-tilled soil from October 1999 to November 2002 as influenced by cover crops.

	Net soil total N content† in strip-tilled soil at various depths, cm		
Cover crop‡	0–15	15–30	0–30
	kg N ha^{-1}		
Weeds	–247d§	–26c	–273c
Rye	22c	25bc	47b
Vetch	144b	159a	303a
Vetch + rye	244a	65b	309a

† Net soil total N content = Average soil total N content for a treatment from April 2000 to November 2002 – soil total N content in October 1999.

‡ Cover crops are rye, cereal rye; vetch, hairy vetch; vetch + rye, hairy vetch and rye biculture; and weeds, winter weeds.

§ Numbers followed by different letter within a column are significantly different at $P \leq 0.05$ by the least square means test.

N inputs with vetch and vetch + rye than with rye and weeds and from N fertilization increased accumulation of soil residual N and therefore STN. Higher STN levels with legume than with non-legume cover crops and the no cover crop treatment (Hargrove, 1986, McVay et al., 1989) or with than without N fertilization (Liang and Mackenzie, 1992; Gregorich et al., 1996; Omay et al., 1997) due to increased crop N inputs had been known. Although N fertilization with cover crops increased total crop N input compared with no N fertilization and the weed treatment (Table 1), the influence of cover crops was more than the influence of N fertilization in increasing STN content (Fig. 3 and 4). Since STN levels were similar between vetch and vetch + rye in tilled and non-tilled soils (Fig. 3), vetch can be replaced by vetch + rye to maintain soil N storage, if vetch increases the potential for N leaching compared with rye (Meisinger et al., 1990; McCracken et al., 1994). Similarly, nonsignificant differences in STN levels (Table 3, Fig. 4) and cotton and sorghum N uptake (Table 1) between 60 and 65 and 120 to 130 kg N ha^{-1} suggests that recommended N fertilization rates to cotton and sorghum can be reduced by half to maintain soil N storage, optimize crop yield and N uptake (Sainju et al., 2006), and reduce the cost of N fertilization and the potential for N leaching (Owens et al., 1994; Sexton et al., 1996; Pang et al., 1998). This could be possible provided that N mineralization also increases with increased N storage. Nitrogen storage increased with N fertilization when the fertilizer was incorporated into the soil using chisel till (Fig. 4). Greater biomass N input due to increased N fertilization (Table 1), followed by incorporation of residue into the soil to a greater depth could have increased N storage in chisel-tilled soil. Doubling the N rates (60 to 65 vs. 120 to 130 kg N ha^{-1}), however, did not increase biomass N input and STN levels (Table 1, Fig. 4).

Since cover crop × N fertilization × soil depth × sampling time interaction was not significant for STN content (Table 2), the effects of cover crops and N fertilization rates in storing soil N at the 0- to 30-cm depth [where N was mostly stored and data on original (1999) soil N content were available] was evaluated by the amount of STN gained or lost by deducting the original STN content in October 1999 from the average STN content from Octber 1999 to November 2002 for each treatment in tilled and nontilled soils (Tables 4 and 5). From October 1999 to November 2002, the weed treatment with or without N fertilization lost STN at 0 to 30 cm from 143 to 330 kg N ha^{-1} in no-tilled soil and had a loss of 210 kg N ha^{-1} to a gain of 121 kg N ha^{-1} in chisel-tilled soil (Table 4). Similarly, with or without N fertilization, the rye treatment had a loss of 18 kg N ha^{-1} to a gain of 81 kg N ha^{-1} of STN in no-tilled soil and a gain of 133 to 274 kg N ha^{-1} in chisel-tilled soil. The vetch and vetch + rye treatments gained STN from 258 to 323 kg N ha^{-1} in no-tilled soil and from 214 to 315 kg N ha^{-1} in chisel-tilled soil. This accounted to increased N storage rates from 86 to 108 kg N ha^{-1} yr^{-1} with vetch and vetch + rye treatments in no-tilled soil and from 71 to 105 kg N ha^{-1} yr^{-1} in chisel-tilled soil. Gains in STN with vetch and vetch + rye were greater with N fertilization than without. In strip-tilled soil, the weed treatment lost STN at 273 kg N ha^{-1} but rye, vetch, and vetch + rye treatments gained STN from 47 to 309 kg N ha^{-1} from October 1999 to November 2002 (Table 5). Increase in N storage rates with rye, vetch, and vetch + rye were 16, 101, and 103 kg N ha^{-1} yr^{-1}, respectively, in strip-tilled soil. Therefore, vetch and vetch + rye can store soil N better than rye and weeds because of greater crop N inputs returned to tilled and nontilled soils. Without enough residue N input and N cycling, soil N level will be reduced and N fertilization rate will have to be increased for sustainable crop production.

Increase in N storage rates using cover crops at the 0- to 120-cm depth can further be considered by subtracting averaged STN levels across N fertilization rates and sampling times with cover crops vs. with weeds when the original STN level at that depth was not available. Compared with weeds, increased average STN content at 0 to 120 cm from October 1999 to November 2002 with rye, vetch, and vetch + rye, respectively, was 220, 943, and 750 kg N ha^{-1} in no-tilled soil, 406, 575, and 857 kg N ha^{-1} in strip-tilled soil, and 319, 487, and 305 kg N ha^{-1} in chisel-tilled soil (Fig. 3). This amounted to increased N storage rates of 73, 314, 250 kg N ha^{-1} yr^{-1} in no-tilled soil, 135, 192, and 286 kg N ha^{-1} yr^{-1} in strip-tilled soil, and 106, 162, 102 kg N ha^{-1} yr^{-1} in chisel-tilled soil at 0 to 120 cm with rye, vetch, and vetch + rye, respectively, compared with weeds. This shows that, although all cover crops can increase soil N storage compared with weeds, vetch and vetch + rye can even store more N in tilled and nontilled soils than rye, regardless of N fertilization rates. Greater soil N storage will lead

to sustained crop production and improved soil, water, and air quality by increasing soil organic matter and reducing the potential for N leaching and N_2O emission, a devastating greenhouse gas responsible for global warming.

SUMMARY AND CONCLUSIONS

Results of this study showed that cover crops and N fertilization increased the amount of cover crop, cotton, and sorghum residue N returned to the soil and STN content compared with winter weeds and no-N fertilization in tilled and nontilled soils. Increases in residue N and STN content were greater in vetch and vetch + rye with N fertilization than in rye and weeds with or without N fertilization. Because of higher N supply, vetch and vetch + rye increased soil N storage compared with rye. The 60 to 65 kg N ha^{-1} increased N storage compared with 0 kg N ha^{-1} only at the surface layer in chisel-tilled soil. Vetch and vetch + rye increased N storage at 71 to 108 kg N ha^{-1} yr^{-1} compared with N loss with winter weeds in tilled and nontilled soils, regardless of N fertilization rates. Therefore, vetch and vetch + rye can be used to sustain cotton and sorghum N uptake, increase soil N storage, and reduce the cost and rate of N fertilization better than rye or weeds. Because of similar cotton and sorghum residue N and STN levels, vetch monoculture can be replaced by vetch + rye biculture to sustain crop N uptake, to maintain soil N storage in tilled and nontilled soils, and to reduce the potential for N leaching following vetch compared with following rye or weeds. Similarly, nonsignificant differences in cotton and sorghum residue N and STN levels between 60 and 65 and 120 to 130 kg N ha^{-1} indicates that N fertilization rate can be reduced by half to reduce the cost of N fertilization and the potential for N leaching. Increased soil N storage will ultimately lead to improved soil productivity and environmental quality by sustaining crop production and reducing the potentials for N leaching and N_2O emission.

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