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# Tillage, Cover Crops, and Nitrogen Fertilization Effects on Cotton and Sorghum Root Biomass, Carbon, and Nitrogen

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## ABSTRACT

**Management practices may influence cotton (*Gossypium hirsutum* L.) and sorghum [*Sorghum bicolor* (L.) Moench)] root C and N inputs for improving soil quality. We examined the influence of three tillage practices [no-till (NT), strip till (ST), and chisel till (CT)], four cover crops {legume [hairy vetch (*Vicia villosa* Roth)], nonlegume [rye (*Secale cereale* L.)], biculture of legume and nonlegume (vetch and rye), and no cover crops (winter weeds)}, and three N fertilization rates (0, 60–65, and 120–130 kg N ha$^{-1}$) on cotton and sorghum root C and N from the 0- to 120-cm soil depth. A field experiment was conducted in a Dothan sandy loam (fine-loamy, kaolinitic, thermic, Plinthic Kandiudults) from 2000 to 2002 in central Georgia. Root C and N at 0 to 15 cm were greater in NT than in ST and CT in 2000 cotton and 2001 sorghum, but at 30 to 60 cm they were greater in ST than in NT and CT in 2000 cotton. Root C and N at 0 to 15 cm were also greater with vetch and rye biculture than with vetch and weeds in 2001 sorghum. Total root C and N at 0 to 120 cm were greater in ST with vetch than in ST with rye or in CT with weeds in 2000 cotton. In contrast, total root N was greater in NT with rye than in ST with rye or CT with vetch in 2001 sorghum and 2002 cotton. Total root N was also greater in CT with 60 kg N ha$^{-1}$ than in NT or CT with 120 kg N ha$^{-1}$ in 2000 cotton, but was greater in ST with 60 kg N ha$^{-1}$ than in NT with 0 kg N ha$^{-1}$ or CT with 120 kg N ha$^{-1}$ in 2002 cotton. The NT or ST with vetch and rye cover crops and 60 kg N ha$^{-1}$ may increase cotton and sorghum root C and N compared with CT with no cover crops and N fertilization, thereby helping to improve soil quality and productivity.**

ROOT GROWTH explores the amount of water and nutrient available in the soil and can influence crop yield (Merrill et al., 1996, 2002; Stone et al., 2001). Although much is known about root length density and distribution in the soil, little information exists about crop root biomass and amount of C and N supplied by them. Since aboveground biomass of plants is usually harvested for animal feed (hay), litter, or fuel, roots form the main source of C in maintaining soil organic matter. The amount of C and N supplied by roots can be significant for maintaining or improving soil organic matter. As much as 7 to 43% of the total aboveground and belowground plant biomass can be contributed by roots (Kuo et al., 1997a, 1997b). Roots can supply from 400 to 1460 kg C ha$^{-1}$ during a growing season (Qian and Doran, 1996; Kuo et al., 1997a). Liang et al. (2002) found that roots contributed as much as 12% of soil organic C, 31% of water soluble C, and 52% of microbial biomass C within a growing season. Roots may play a dominant role in soil C and N cycles (Wedin and Tilman, 1990; Gale et al., 2000a; Puget and Drinkwater, 2001) and may have relatively greater influence on soil organic C and N levels than the aboveground plant biomass (Milchumas et al., 1985; Boone, 1994; Norby and Cotrufo, 1998). Balesdent and Balabane (1996) observed that corn (*Zea mays* L.) roots contributed 1.6 times more C to soil organic C than did stover. Root-derived C is retained and forms more stable aggregates than shoot-derived C (Gale et al., 2000a, 2000b). Growing plants tend to maintain soil organic C level by continuously supplying C from roots compared with bare soil, which tends to decrease it (Haider et al., 1993; Sanchez et al., 2002). While C accumulation in roots may have resulted from C sequestration in aboveground biomass and its partitioning in belowground biomass, N accumulation may have resulted either from N uptake from the soil and/or fixed from the atmosphere, depending on crop species.

Rhizodeposition, such as root exudates, mucilages, and sloughed cells, may be a significant source of soil organic C (Buyanovsky et al., 1986; Balesdent and Balabane, 1996). Helal and Sauerbeck (1987) estimated that the amount of C released from roots as rhizodeposit could be more than 580 kg C ha$^{-1}$, which increases microbial activity and influence N mineralization in the soil (Bakken, 1990; Texier and Biles, 1990). Carbon contribution from corn root biomass and rhizodeposition to soil organic C can be as much as 1.7 to 3.5 times greater than from stover (Allmaras et al., 2004; Wilts et al., 2004). Therefore, C input both from root biomass and rhizodeposit should be taken into account when C contribution from roots is considered for maintaining or increasing soil organic matter.

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**Abbreviations:** CT, chisel till; MT, moldboard till; NT, no-till; ST, strip-till.

Since root systems of crops develop before aboveground growth (Klepper, 1992) and soil and climatic factors can influence root growth (Kuchenbuch and Barber, 1987; Zobel, 1992), management practices such as tillage, cover crops, and N fertilization can alter root growth, biomass yield, and C and N accumulations by modifying soil moisture, temperature, and nutrient application and redistribution (Crozier et al., 1999; Merrill et al., 1996, 2002; Qin et al., 2004). Several researchers have observed greater root length density in wheat (*Triticum aestivum* L.), corn, and alfalfa (*Medicago sativa* L.) in NT than in conventional till (Baligar et al., 1996; Merrill et al., 1996; Rasse and Smucker, 1996). They attributed this due to superior moisture conservation and cooler temperature at the soil surface in NT than in conventional till that stimulated root growth during the growing season in the summer. Several other researchers have found greater root density in NT than in CT in the surface soil, especially at the 0- to 5-cm depth (Wulfsohn et al., 1996; Qin et al., 2004), probably due to stratification of immobile nutrients such as P (Holanda et al., 1998; Crozier et al., 1999). In contrast, CT resulted in greater root growth at deeper soil layers (Chan and Mead, 1992; Qin et al., 2004).

Cover cropping can promote root growth of the succeeding crop compared with no cover cropping by increasing the amount of plant residue returned to the soil, thereby increasing soil organic matter level, decreasing bulk density, influencing soil temperature, and increasing the density of biopores in the soil profile where roots of succeeding crops can grow even in the root restricting layers (Box, 1996; Karlen, 1990). Williams and Weil (2004) observed increased root growth of soybean [*Glycine max* (L.) Merr.] in root channels made by decomposing cover crop roots in the compacted soil, which increased soybean yields even during drought condition. Deep-rooted cover crops can alleviate soil compaction problems by establishing root channels that increase soil infiltration rate (Meek et al., 1990), which benefited root systems and yields of corn (Rasse and Smucker, 1996) and lettuce (*Lettuce sativa* L.) (Stirzaker and White, 1995). Fertilization with N also may increase crop root growth by increasing soil N availability (Weston and Zandstra, 1989; Garton and Widders, 1990). Sainju et al. (2001) observed that tomato (*Lycopersicon esculentum* Mill.) root growth was greater with hairy vetch and crimson clover cover crops and 90 kg N ha$^{-1}$ than with no cover crops or N fertilization due to increased amount of N availability in the soil. Tillage can interact with cover crop and N fertilization in crop root growth (Sainju et al., 2000).

While information exists on the influence of tillage and N fertilization on crop root growth, little is known about the combined effects of tillage, cover crops, and N fertilization on root biomass yield and C and N accumulations in cotton and sorghum. Changes in root growth and C and N accumulations in them due to management practices may alter soil properties and yield of succeeding crops. We hypothesized that conservation tillage, such as NT or ST, with hairy vetch and rye cover crop mixture, and 60 to 65 kg N ha$^{-1}$ will increase root biomass yield and C and N accumulations in cotton and sorghum compared with CT with no cover crop and N fertilization. Our objectives were to (i) examine the influence of tillage, legume and nonlegume cover crops, and N fertilization rates on root biomass yield and C and N accumulations in cotton and sorghum from 2000 to 2002; and (ii) determine management practices consisting of tillage, cover crops, and N fertilization rates that promote cotton and sorghum root biomass yield and C and N accumulations and help to improve soil quality and crop productivity.

## MATERIALS AND METHODS

### Site Description and Experimental Design

The experiment was part of the long-term study of the effects of tillage, cover crops, and N fertilization rates on crop yields and soil quality conducted in 1995 at the Agricultural Research Station farm, Fort Valley State University, Fort Valley, GA. Treatments consisted of three tillage practices [no-till (NT), chisel till (CT), and moldboard till (MT)], two cover crops (hairy vetch and winter weeds or no cover crop), and three N fertilization rates (0, 60–90, and 120–180 kg N ha$^{-1}$) arranged in a split-split plot design in randomized complete block with six replications. While NT plots were left undisturbed except for drilling cover crop and corn seeds, CT plots were harrowed to a depth of 10 to 15 cm, followed by chiseling to a depth of 15 to 20 cm and leveling with a S-tine harrow. Similarly, MT plots were harrowed to a depth of 10 to 15 cm, followed by moldboard plowing to a depth of 15 to 20 cm and leveling with a S-tine harrow. Tillage was the main plot, cover crop split plot, and N rate split-split plot treatment. Tomato was grown from 1995 to 1997 and silage corn from 1998 to 1999. The soil was a Dothan sandy loam with pH of 6.5 and sand content of 650, silt 250, and clay 100 g kg$^{-1}$ soil at the 0- to 30-cm depth. The clay content increased to 250 g kg$^{-1}$ below 30 cm. The organic C in the soil sampled in October 1995 was 8.8 g kg$^{-1}$ and organic N 0.62 g kg$^{-1}$ at the 0- to 30-cm depth. Temperature and rainfall data were collected from a weather station, 20 m from the experimental site.

After corn harvest in October 1999, three replicates of winter weeds or no cover crop treatment were replaced by rye cover crop and three replicates of hairy vetch were replaced by hairy vetch and rye biculture. In April 2000, the MT treatment was replaced by ST, which was considered as reduced till. In ST, rows were subsoiled to a 35-cm depth in a narrow strip of 30 cm width for planting cotton and sorghum, thereby leaving the area between rows undisturbed. The surface tilled zone is leveled by coulters behind the subsoiler. The NT and CT treatments were continued without any change since started from 1995. Nitrogen rates of 0, 60 to 90, and 120 to 180 kg N ha$^{-1}$ were replaced by 0, 60 to 65, and 120 to 130 kg N ha$^{-1}$, respectively, according to the recommended N rates for cotton (120 kg N ha$^{-1}$) and sorghum (130 kg N ha$^{-1}$) in central Georgia. Thus, the treatments reestablished in April 2000 consisted of three tillage practices (NT, ST, and CT), four cover crops (hairy vetch, rye, hairy vetch and rye biculture, and winter weeds or no cover crop), and three N fertilization rates (0, 60–65, and 120–130 kg N ha$^{-1}$). These were arranged in a split-split plot design in randomized complete block, with tillage as the main plot, cover crop as the split plot, and N fertilization rate as the split-split plot treatment. Each treatment had three replications. The split-split plot size was 7.2 by 7.2 m.

## Field Methods

Cover crops were planted in October–November 1999 to 2001 in the same plot every year. Hairy vetch seeds were drilled at 28 kg ha$^{-1}$ after inoculating with *Rhizobium leguminosarum* (bv. viceae) and rye seeds at 80 kg ha$^{-1}$, using a row spacing of 15 cm. In the hairy vetch and 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 used as recommended by Clark et al. (1994). Cover crops were drilled in the plots without any tillage because previous studies have shown that cover crop aboveground biomass yields and C and N accumulations were not significantly influenced by tillage practices (Sainju et al., 2001, 2002). No fertilizers, herbicides, or insecticides were applied to cover crops.

In April 2000 to 2002, cover crop biomass yield was determined by harvesting plant samples from two 1-m$^2$ areas randomly within each plot and weighed in the field. After mixing the sample thoroughly, a subsample (≈100 g fresh wt.) was collected for determinations of dry matter yield and C and N concentrations and the rest was returned to the harvested area where it was spread uniformly by hand. In the plots without cover crop, winter weeds, dominated by henbit (*Lamium amplexicaule* L.) and cut-leaf evening primrose (*Oenothera laciniata* Hill), were collected using the same procedure. Plants 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 break the plants into smaller pieces and distribute the residue evenly within the plots. In NT and ST plots, cover crops were killed by spraying 3.36 kg a.i. ha$^{-1}$ of glyphosate [*N*-(phosphonomethyl) glycine]. In CT plots, cover crops were killed by disc harrowing and chisel plowing. Residues were allowed to decompose in the soil for 2 wk before cotton and sorghum planting.

At the time of planting cotton and sorghum in May 2000 to 2002, P {from triple superphosphate [$Ca(H_2PO_4)_2$]} fertilizer at 36 kg ha$^{-1}$ for cotton and 40 kg ha$^{-1}$ for sorghum and K [from muriate of potash (KCl)] fertilizer at 75 kg ha$^{-1}$ for cotton and 80 kg ha$^{-1}$ for sorghum were broadcast in all plots based on the soil test and crop requirement. At the same time, B [from boric acid ($H_3BO_3$)] fertilizer at 0.23 kg ha$^{-1}$ for cotton was also broadcast. Nitrogen fertilizer as $NH_4NO_3$ was applied at 0, 60, and 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 0, 65, and 130 kg N ha$^{-1}$ for sorghum in 2001, two-thirds of which was broadcast at planting and other one-third broadcast 6 wk later. The fertilizers applied at planting were left at the soil surface in NT, partly incorporated in ST during subsoiling, and completely incorporated into the soil in CT by chisel plowing. While NT plots were left undisturbed except for drilling cover crop seeds and planting cotton and sorghum, ST plots were subsoiled in rows, 0.9 m apart, where cotton and sorghum were planted. In CT, plots were harrowed, chiseled, and leveled. Irrigation was applied immediately after fertilization to solubilize the fertilizer in the soil and to reduce the loss due to volatilization in NT and ST plots. In CT, plots were tilled immediately after fertilization to mix the fertilizer in the soil, followed by irrigation. For N fertilizer applied 6 wk after planting, irrigation was applied immediately after fertilization to solubilize the fertilizer in the soil.

Following tillage, glyphosate-resistant cotton (cv. DP458BR) at 8 kg ha$^{-1}$ in 2000 and 2002 and sorghum (cv. 9212Y) 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 planter. Although planning was made to plant cotton continuously from 2000 to 2002, sorghum was planted in 2001 to reduce the incidence of diseases and pests. Cotton was sprayed with glyphosate herbicide at 3.36 kg a.i. ha$^{-1}$ to control weeds immediately after planting and during cotton growth. For sorghum, atrazine [6-chloro-*N*-ethyl-*N′*-(1-methylethyl)-1,3,5-triazine-2,4-diamine] at 1.5 kg a.i. ha$^{-1}$ and metolachlor [(2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl) acetamide] at 1.3 kg a.i. ha$^{-1}$ were applied within a day after planting to control post emergence of weeds. Aphids (*Aphis gossypii* Glover) in cotton were controlled by spraying endosulfan (6, 7, 8, 9, 10-10-hexachloro-1, 5, 5a, 6, 9, 9a-hexahydro-6, 9 methano-2, 4, 3 benzodioxathiepin-3-oxide) at 0.6 kg a.i. ha$^{-1}$. Cotton was also sprayed with the growth regulator, Pix (1, 1-dimethyl-piperdinium chloride), at 0.8 kg a.i. ha$^{-1}$ at 2 mo after planting to control vegetative growth and the defoliant, Cottonquik [1-aminomethanamide dihydrogen tetraoxosulfate ethephon (2-chloroethyl) phosphoric acid], was sprayed at 2.8 L ha$^{-1}$ at 2 to 3 wk before lint and seed harvest to defoliate leaves. Irrigation (equivalent to 25 mm rain at a time using reel rain gun) was applied immediately after planting and during dry periods to prevent moisture stress.

In October–November 2000 and 2002, cotton (lint + seed) yield was determined by hand harvesting two central rows (7.2 by 1.8 m$^2$) and weighing. Lint yield was determined by separating lint from seed after ginning. In November 2001, sorghum grain yield was determined by hand harvesting heads from two central rows (7.2 by 1.8 m$^2$), separating grains, and weighing. After harvest, cotton and sorghum straw (leaves and stems) were mowed and residues were left at the soil surface.

Immediately after mowing the cotton and sorghum residues in November 2000 to 2002, soil samples were collected from the 0- to 120-cm depth from each plot using a hydraulic probe (5 cm i.d. and 120 cm long) attached to a tractor to collect root biomass. Samples were collected from four holes randomly, two from the rows and other two between the rows, within each plot. These were separated into 0- to 15-, 15- to 30-, 30- to 60-, 60- to 90-, and 90- to 120-cm lengths to represent each depth, composited within a depth, and stored at 4°C until roots were separated from the soil. In measuring the root biomass yield and C and N accumulations in cotton and sorghum, it has been assumed that roots of these crops distribute uniformly in the soil profile within the plot. As a result, it is estimated that root biomass taken at different depths within 0- to 120-cm from four soil cores randomly within the plot and composited within a depth represents the biomass yield of roots at that depth. Because of the difficulty of taking root biomass samples from 0- to 120-cm in the field, unless the whole plot is dug out, we assumed that the core method will give a fairly good estimate of measuring root biomass yield and C and N accumulations. In November 2002, one additional core soil sample was taken from the 0- to 120-cm depth from each plot, divided into segments to represent various depths as above, and bulk density and clay contents at each depth as influenced by treatments were measured.

## Laboratory Analysis

Soil samples collected for determining root biomass were thoroughly washed with water in a nest of 1.0- and 0.5-mm sieves. About 500 g of soil was washed at a time with a fine spray of water at the top and bottom sieves and roots retained in both sieves were picked by tweezers and collected in a plastic bag. As a result, all of the course and most of the fine roots were collected. The process was repeated several times until all soil from a plot was washed and roots separated. Roots were oven-dried at 60°C for 3 d and weighed. Biomass yield determination of roots at a depth was determined as dry matter weight of the roots in the soil volume at that depth. Total biomass weight of roots from the 0- to 120-cm depth was calculated by summing up root biomass at individual depths. Roots were ground and passed through a 1-mm sieve for C and N determinations.

Nitrogen concentration (g N $kg^{-1}$ plant dry wt.) in roots was determined by the $H_2SO_4$–$H_2O_2$ method as described by Kuo et al. (1997b). Carbon concentration (g C $kg^{-1}$ plant dry wt.) was determined by the Walkley-Black method (Nelson and Sommers, 1996), assuming all plant C was oxidized during digestion. Similarly, N and C concentrations in aboveground cover crop biomass were determined as above. Carbon and N accumulations (kg $ha^{-1}$) in cotton and sorghum roots and cover crops were determined by multiplying dry matter weight by C and N concentrations. As with root biomass yield, total C and N accumulations in root biomass of cotton and sorghum from the 0- to 120-cm depth was calculated by adding C and N accumulations at individual depths. Soil bulk density was measured by drying soil cores of various depths at 105°C, weighing, and dividing the weight of the core by its volume. Clay content was determined by the modified hydrometer method (Gee and Bauder, 1986).

### Data Analysis

For analyzing the effects of tillage, cover crop, N fertilization rate, and soil depth on root biomass yield and C and N accumulations in cotton and sorghum in each year, tillage was considered as the main plot, cover crop as the split plot, N fertilization rate as the split-split plot, and soil depth as the split-split-split plot treatment. Data for root biomass yield, C and N concentrations, and C and N accumulations were analyzed using the MIXED procedure of SAS after testing for homogeneity of variance (Littell et al., 1996). Sources of variation included tillage, cover crop, N fertilization rate, soil depth, and their interactions. These were considered as fixed effects while replication and tillage × replication interactions were considered as random effects. Since data for root biomass yield and C and N accumulations cannot be averaged across depth, only values for treatments that interacted with soil depth were analyzed. For measuring the effects of treatments and their interactions, data for total root biomass yield and C and N accumulations from the 0- to 120-cm depth were used, where tillage was considered as the main plot, cover crop as the split plot, and N fertilization rate as the split-split plot treatment. Data were analyzed by the MIXED procedure as above. Means were separated by using the least square means test when treatments and their interactions were significant. Statistical significance was evaluated at $P \leq 0.05$.

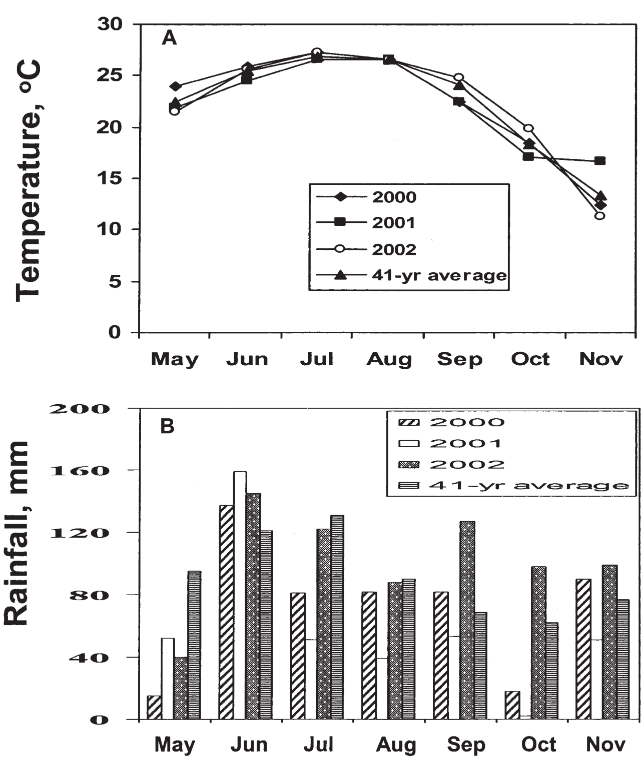


**Fig. 1. (A) Mean monthly temperature and (B) total monthly rainfall from May to November in 2000, 2001, 2002, and the 41-yr average near the study site.**

## RESULTS

### Climate

Average monthly temperature in May was higher in 2000 than in 2001, 2002, and the 41-yr average, but in September and October the temperature was higher in 2002 (Fig. 1A). Total monthly rainfall from July to November was higher in 2002 than in 2000 and 2001 (Fig. 1B). Total rainfall during the growing season from May to November was also higher in 2002 (719 mm) than in 2000 (505 mm), 2001 (354 mm), and the 41-yr average (645 mm). The temperature and rainfall during the growing season may influence growth, biomass yield, and C and N accumulations in cotton and sorghum roots.

### Cover Crop Biomass Yield and Carbon and Nitrogen Accumulations

Aboveground biomass yield and C accumulation were greater in cover crops than in winter weeds (Table 1). Biomass yield and C accumulation were greater in rye

**Table 1. Effects of years and cover crop species on aboveground biomass yield and C and N accumulations in cover crops averaged across tillage and N fertilization rates.**

| Year | Cover crop† | Aboveground biomass yield | Concentration | | Accumulation | | C/N ratio |
|---|---|---|---|---|---|---|---|
| | | | C | N | C | N | |
| | | Mg $ha^{-1}$ | g $kg^{-1}$ | | | | |
| 2000 | WW | 1.65 | 334 | 15 | 551 | 25 | 22 |
| | R | 6.07 | 338 | 15 | 2355 | 91 | 26 |
| | V | 5.10 | 354 | 33 | 1805 | 168 | 11 |
| | VR | 8.18 | 330 | 38 | 2699 | 311 | 9 |
| 2001 | WW | 0.75 | 353 | 20 | 265 | 15 | 18 |
| | R | 3.81 | 404 | 8 | 1539 | 30 | 51 |
| | V | 2.44 | 359 | 32 | 876 | 78 | 11 |
| | VR | 5.98 | 404 | 14 | 2416 | 84 | 29 |
| 2002 | WW | 1.25 | 338 | 18 | 423 | 23 | 19 |
| | R | 2.28 | 392 | 11 | 894 | 25 | 36 |
| | V | 5.16 | 326 | 36 | 1682 | 186 | 9 |
| | VR | 5.72 | 334 | 33 | 1968 | 188 | 10 |
| LSD(0.05) | | 0.96 | 34 | 7 | 480 | 23 | 6 |
| Means | | | | | | | |
| 2000 | | 5.25a‡ | 352a | 25ab | 1848a | 131a | 14ab |
| 2001 | | 3.25b | 380a | 19b | 1235b | 62b | 20a |
| 2002 | | 3.60b | 350a | 32a | 1230b | 115a | 11b |
| | WW | 1.22c | 342b | 18b | 417c | 22c | 19b |
| | R | 4.07b | 395a | 12b | 1608b | 49c | 33a |
| | V | 4.23b | 347b | 34a | 1468b | 144b | 10c |
| | VR | 6.63a | 359b | 28a | 2380a | 186a | 13bc |

† R, rye; V, hairy vetch; VR, hairy vetch and rye biculture; and WW, winter weeds.

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

than in hairy vetch in 2000 and 2001 but were greater in vetch than in rye in 2002. The vetch and rye biculture had greater biomass yield and C accumulation than vetch and rye monocultures. Nitrogen concentration was higher in vetch and biculture than in rye and winter weeds, except in 2001. As a result, N accumulation was greater but C/N ratio was lower in vetch and biculture than in rye and weeds.

## Cotton Root Biomass and Carbon and Nitrogen in 2000

Cotton root biomass yield and C and N accumulations in 2000 varied with tillage and soil depth (Fig. 2). As a result, depth and tillage × depth interactions were significant ($P \leq 0.05$) (Table 2). Root biomass yield, averaged across cover crops and N fertilization rates, was significantly greater in NT than in ST and CT at 0 to 15 cm, but was greater in ST than in NT and CT at 30 to 60 cm (Fig. 2A). Carbon concentration in root biomass was greater in NT and CT than in ST at 15 to 30 cm, but was greater in ST than in CT at 60 to 90 cm and greater in ST than in NT and CT at 90 to 120 cm (Fig. 2B). Similarly, N concentration in root biomass was greater in ST than in CT at 60 to 90 cm (Fig. 2C). Carbon accumulation in root biomass was greater in ST than in NT at 30 to 60 cm (Fig. 2D). Nitrogen accumulation was greater in NT than in ST at 0 to 15 cm but was greater in ST than in NT and CT at 30 to 60 cm (Fig. 2E). The C/N ratio in root biomass was not influenced by tillage. Averaged across tillage, cover crops, and N rates, cotton root biomass yield and C accumulation were greater at 30 to 60 cm than at other depths (Table 3). Nitrogen accumulation was greater at 0 to 15 and 30 to 60 cm than at 90 to 120 cm and C concentration was greater at 30 to 120 cm than at 0 to 15 cm.

For the total root biomass yield and C and N accumu-

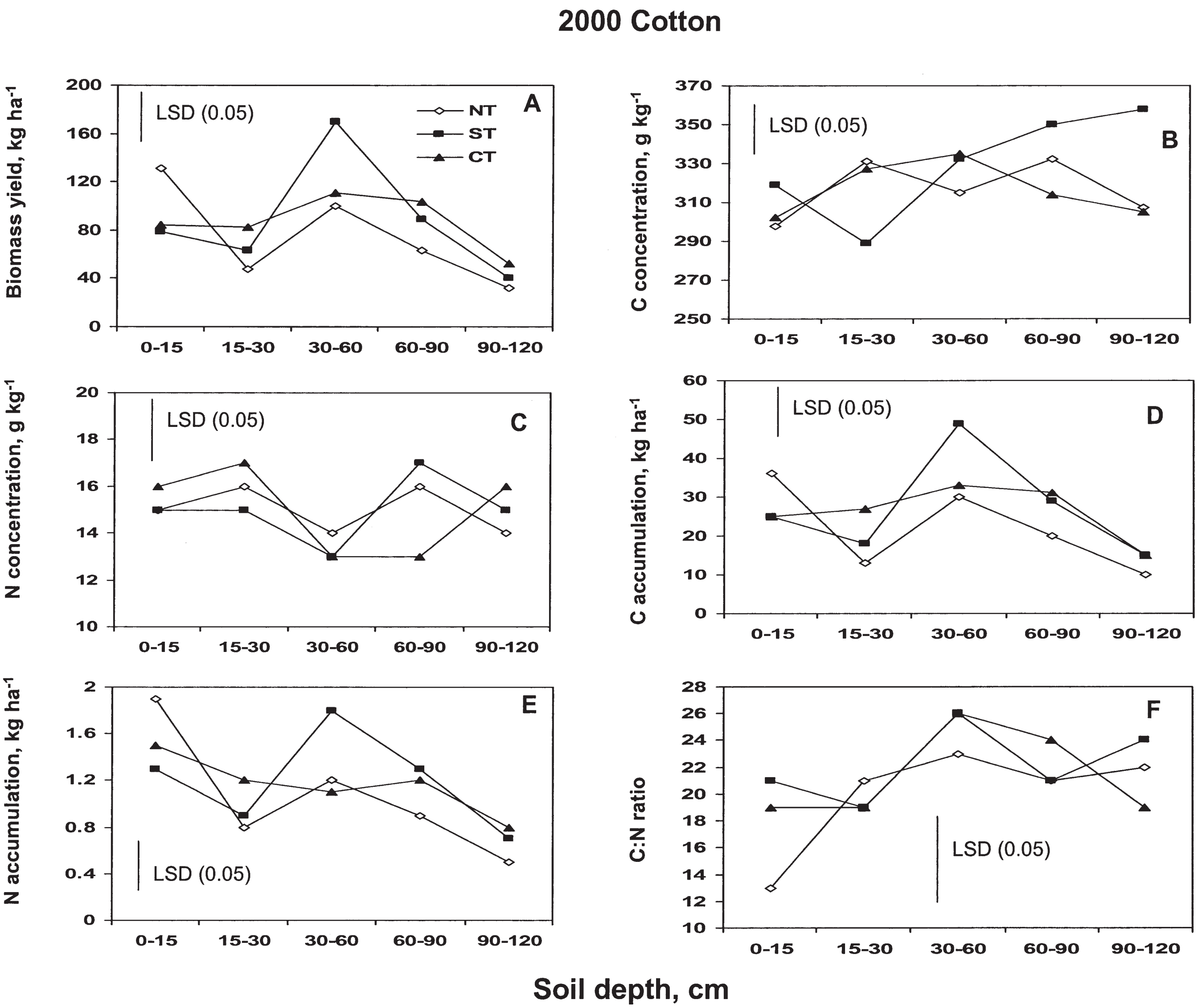


Fig. 2. Effect of tillage on (A) biomass yield, (B) C concentration, (C) N concentration, (D) C accumulation, (E) N accumulation, and (F) C/N ratio of cotton roots from the 0- to 120-cm depth in 2000. CT denotes chisel till; NT, no-till; and ST, strip-till. LSD(0.05) is the least significant difference between treatments at $P = 0.05$.

**Table 2. Analysis of variance for root biomass yield, C and N concentrations, and C and N accumulations in 2000 cotton, 2001 sorghum, and 2002 cotton.**

| | 2000 cotton† | | | | | 2001 sorghum† | | | | | 2002 cotton† | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Source | RBY | RCC | RNC | RCA | RNA | RBY | RCC | RNC | RCA | RNA | RBY | RNC | RNA |
| Tillage (T) | NS‡ | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| Cover crop (C) | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| T × C | NS | § | NS | NS | NS | NS | NS | NS | NS | NS | NS | * | NS |
| N fertilization (F) | NS | NS | * | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| T × F | § | NS | NS | § | § | NS | NS | NS | NS | NS | NS | NS | NS |
| C × F | NS | * | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| T × C × F | NS | * | ** | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| Soil depth (D) | * | § | ** | * | * | *** | * | *** | *** | *** | *** | *** | *** |
| T × D | * | *** | * | * | * | *** | NS | NS | *** | *** | NS | NS | NS |
| C × D | NS | NS | NS | NS | NS | *** | NS | NS | * | *** | NS | NS | NS |
| T × C × D | NS | NS | NS | NS | NS | NS | NS | + | NS | NS | NS | NS | NS |
| T × F × D | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| C × F × D | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| T × C × F × D | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.
*** Significant at $P \leq 0.001$.
† RBY, root biomass yield; RCC, root C concentration; RNC, root N concentration; RCA, root C accumulation; and RNA, root N accumulation.
‡ Not significant.
§ Significant at $P \leq 0.10$.

lations from the 0- to 120-cm depth, tillage interacted significantly ($P \leq 0.05$) with cover crop and N fertilization, but the main treatments were not significant (Table 4). Total root biomass yield and C accumulation, averaged across N rates, were greater in ST with hairy vetch than in ST with rye or CT with winter weeds (Table 5). Total N accumulation was greater in ST with vetch than in NT with vetch, ST with rye, CT with weeds, and CT with vetch and rye biculture. Total biomass yield, averaged across cover crops, was greater in CT with 60 kg N ha$^{-1}$ than in NT with 120 kg N ha$^{-1}$ (Table 6). Similarly, total C and N accumulations were greater in CT with 60 kg N ha$^{-1}$ than in NT with 120 kg N ha$^{-1}$, ST with 60 kg N ha$^{-1}$, or CT with 120 kg N ha$^{-1}$.

**Table 3. Distribution of root biomass yield and C and N accumulations of cotton and sorghum at the 0- to 120-cm depth averaged across tillage, cover crops, and N fertilization rates from 2000 to 2002.**

| Soil depth | Root biomass yield | Concentration C | Concentration N | Accumulation C | Accumulation N | C/N ratio |
|---|---|---|---|---|---|---|
| cm | kg ha$^{-1}$ | g kg$^{-1}$ | | kg ha$^{-1}$ | | |
| | | **2000 Cotton** | | | | |
| 0–15 | 98b† | 306b | 16a | 30b | 1.6a | 19a |
| 15–30 | 65bc | 315ab | 16a | 20c | 1.0ab | 20a |
| 30–60 | 125a | 327a | 14a | 41a | 1.8a | 23a |
| 60–90 | 87b | 332a | 15a | 27b | 1.3ab | 22a |
| 90–120 | 43c | 327a | 15a | 14c | 0.7b | 22a |
| | | **2001 Sorghum** | | | | |
| 0–15 | 202a | 305b | 15b | 62a | 3.0a | 20a |
| 15–30 | 44b | 325a | 19a | 14b | 0.8b | 17a |
| 30–60 | 56b | 332a | 17ab | 19b | 0.9b | 20a |
| 60–90 | 51b | 309b | 18ab | 16b | 0.9b | 17a |
| 90–120 | 52b | 319ab | 16ab | 17b | 0.8b | 20a |
| | | **2002 Cotton** | | | | |
| 0–15 | 333a | – | 11d | – | 3.6a | – |
| 15–30 | 127bc | – | 20ab | – | 2.5b | – |
| 30–60 | 182b | – | 14cd | – | 2.5b | – |
| 60–90 | 126bc | – | 17bc | – | 2.1b | – |
| 90–120 | 85c | – | 22a | – | 1.9b | – |

† Numbers followed by different letter within a column of a subset are significantly different at $P \leq 0.05$ by the least significant difference test.

## Sorghum Root Biomass and Carbon and Nitrogen in 2001

Similar to cotton roots in 2000, depth, tillage × depth, and cover crop × depth interactions were significant ($P \leq 0.05$) for sorghum root biomass yield and C and N accumulations in 2001 (Table 2). Root biomass yield and C accumulation, averaged across cover crops and N rates, were greater in NT than in ST and CT at 0 to 15 cm (Fig. 3A and 3D). Nitrogen accumulation was greater in NT than in ST at 0 to 15 cm (Fig. 3E). Averaged across tillage and N rates, root biomass yield was greater with vetch and rye biculture than with vetch, rye, and winter weeds (Fig. 4A), but C and N accumulations were greater with biculture than with vetch and weeds at 0 to 15 cm (Fig. 4D and 4E). Averaged across tillage, cover crops, and N rates, root biomass yield and C and N accumulations were three to five times greater at the 0- to 15-cm depth than at the 15- to 120-cm depth, whereas C and N concentrations were greater at the 15- to 30-cm depth than at the 0- to 15-cm depth (Table 3).

Tillage and cover crop also interacted significantly ($P \leq 0.05$) for total root biomass yield and C and N accumulations from 0 to 120 cm in sorghum, but the

**Table 4. Analysis of variance for total root biomass yield and C and N accumulations from the 0- to 120-cm depth in 2000 cotton, 2001 sorghum, and 2002 cotton.**

| | 2000 cotton† | | | 2001 sorghum† | | | 2002 cotton† | |
|---|---|---|---|---|---|---|---|---|
| Source | TRBY | TCA | TNA | TRBY | TCA | TNA | TRBY | TNA |
| Tillage (T) | NS‡ | NS | NS | NS | NS | NS | NS | NS |
| Cover crop (C) | NS | NS | NS | NS | NS | NS | NS | NS |
| T × C | * | * | * | * | * | * | NS | * |
| N fertilization (F) | NS | NS | NS | NS | NS | NS | NS | * |
| T × F | * | * | * | NS | NS | NS | * | * |
| C × F | NS | NS | NS | NS | NS | NS | NS | NS |
| T × C × F | NS | NS | NS | NS | NS | NS | NS | NS |

* Significant at $P \leq 0.05$.
† TRBY, total root biomass yield from 0 to 120 cm; TCA, total root C accumulation from the 0- to 120-cm depth; and TNA, total root N accumulation from 0 to 120 cm.
‡ Not significant.

**Table 5. Effects of tillage and cover crops on total root biomass yield and C and N accumulations from the 0- to 120-cm soil depth averaged across N fertilization rates in 2000 cotton.**

| Tillage† | Cover crop‡ | Total root biomass yield | Total C accumulation | Total N accumulation |
|---|---|---|---|---|
| | | kg ha$^{-1}$ | | |
| NT | WW | 373 | 79 | 3.7 |
| | R | 248 | 72 | 3.7 |
| | V | 210 | 63 | 2.9 |
| | VR | 315 | 99 | 4.4 |
| ST | WW | 423 | 104 | 4.4 |
| | R | 108 | 50 | 2.1 |
| | V | 511 | 137 | 7.4 |
| | VR | 289 | 96 | 4.3 |
| CT | WW | 182 | 54 | 2.6 |
| | R | 453 | 132 | 7.1 |
| | V | 374 | 122 | 4.3 |
| | VR | 218 | 61 | 2.8 |
| LSD(0.05) | | 327 | 82 | 4.1 |

† CT, chisel till; NT, no-till; and ST, strip till.
‡ R, rye; V, hairy vetch; VR, hairy vetch and rye biculture; and WW, winter weeds (no cover crops).

main treatments were not significant (Table 4). Averaged across N rates, total root biomass yield and C and N accumulations were greater in NT with rye than in NT with vetch, ST with rye, or CT with weeds (Table 7). Total N accumulation was also greater in CT with vetch and rye biculture than in NT with vetch, ST with rye, or CT with vetch.

## Cotton Root Biomass and Nitrogen in 2002

In 2002, C concentration in cotton roots was not measured. Only soil depth was significant ($P \leq 0.05$) for cotton root biomass yield, N concentration, and N accumulation (Table 2). Root biomass yield and N accumulation, averaged across tillage, cover crops, and N rates, were greater at the 0- to 15-cm depth than at the 15- to 120-cm depth (Table 3). Root biomass yield was also greater at the 30- to 60-cm depth than at the 90- to 120-cm depth. In contrast, root N concentration was greater at the 90- to 120-cm depth than at the 0- to 15-, 30- to 60-, and 60- to 90-cm depth.

Similar to cotton roots in 2000, tillage × N fertilization interaction was significant ($P \leq 0.05$) for total root biomass yield and N accumulation from 0 to 120 cm, and N fertilization and tillage × cover crop interaction was significant for total N accumulation in cotton roots in 2002 (Table 4). Averaged across N rates, total N accumulation was greater in ST with weeds and NT with rye than in NT with weeds, NT with biculture, and ST with rye (Table 8). Averaged across cover crops, total root biomass yield was greater in ST with 60 kg N ha$^{-1}$ than in NT with 0 kg N ha$^{-1}$ or CT with 120 kg N ha$^{-1}$ (Table 9). Total N accumulation was greater in ST with 60 kg N ha$^{-1}$ than in NT with 0 kg N ha$^{-1}$, ST with 0 kg N ha$^{-1}$, and CT with 60 and 120 kg N ha$^{-1}$. Averaged across tillage and cover crops, total N accumulation was greater with 60 and 120 kg N ha$^{-1}$ than with 0 kg N ha$^{-1}$.

## Soil Bulk Density and Clay Content

Soil bulk density measured in November 2002 varied with tillage and depth (Table 10). Bulk density was significantly ($P \leq 0.05$) lower in NT and CT than in ST at 0 to 15 cm, but was not influenced by tillage below the 15-cm depth. Bulk density usually increased with depth, except at 30 to 60 cm, where it was similar to or lower than at 0 to 15 cm. Clay content increased with depth and was not influenced by tillage, cover crop, and N fertilization.

**Table 6. Effects of tillage and N fertilization rates on total root biomass yield and C and N accumulations from the 0- to 120-cm soil depth averaged across cover crops in 2000 cotton.**

| Tillage† | N fertilization | Total root biomass yield | Total C accumulation | Total N accumulation |
|---|---|---|---|---|
| | | kg ha$^{-1}$ | | |
| NT | 0 | 311 | 99 | 4.2 |
| | 60 | 430 | 98 | 4.9 |
| | 120 | 118 | 37 | 1.9 |
| ST | 0 | 285 | 93 | 4.1 |
| | 60 | 193 | 45 | 2.9 |
| | 120 | 448 | 118 | 5.1 |
| CT | 0 | 250 | 74 | 3.2 |
| | 60 | 485 | 145 | 6.6 |
| | 120 | 184 | 58 | 2.8 |
| LSD(0.05) | | 308 | 87 | 3.5 |

† CT, chisel till; NT, no-till; and ST, strip till.

## DISCUSSION

It is not surprising to see the large effect of depth on root distribution of crops in soil profile as observed by other researchers (Merrill et al., 1996, 2002; Stone et al., 2001; Qin et al., 2004) because of the difference in properties of various soil layers (e.g., Table 10). Although genetic factors can influence root extension (Russell, 1977), soil factors such as structure, water content, nutrient level, temperature, porosity, gaseous diffusivity, and pH can influence root growth (Klepper, 1992; Merrill et al., 1996). The large root biomass and C and N accumulations at 0 to 15 cm compared with lower depths (Table 3) may have resulted from increased organic matter concentration, nutrient and water availability, and aeration, as have been observed by several researchers (Davis et al., 1983; St. John, 1983; Kalisz et al., 1987). The 40 to 60% of the total root biomass yield and C and N accumulations from the 0- to 120-cm depth observed at 0 to 30 cm in this study were somewhat lower than root length density of 60 to 65% reported by some researchers (Wilhelm et al., 1982; Qin et al., 2004). However, increased root biomass yield and C and N accumulations in cotton and sorghum at 30 to 60 cm than at 15 to 30 or 60 to 90 cm could be due to presence of less compacted layer with lower bulk density and increased clay content at this depth (Table 10), which could have held more water for root growth than the overlying 15- to 30-cm layer. Increased soil compaction as measured by increasing bulk density can restrict root growth (Buttery et al., 1998), but increased moisture availability in the subsoil can promote its growth (Merrill et al., 1996; Stone et al., 2001). Although root biomass decreased with depth, except the increase at 30 to 60 cm, presence of roots at 90 to 120 cm suggests that both cotton and sorghum roots can extend beyond the 120-cm depth in the soil. Sorghum roots have been found to

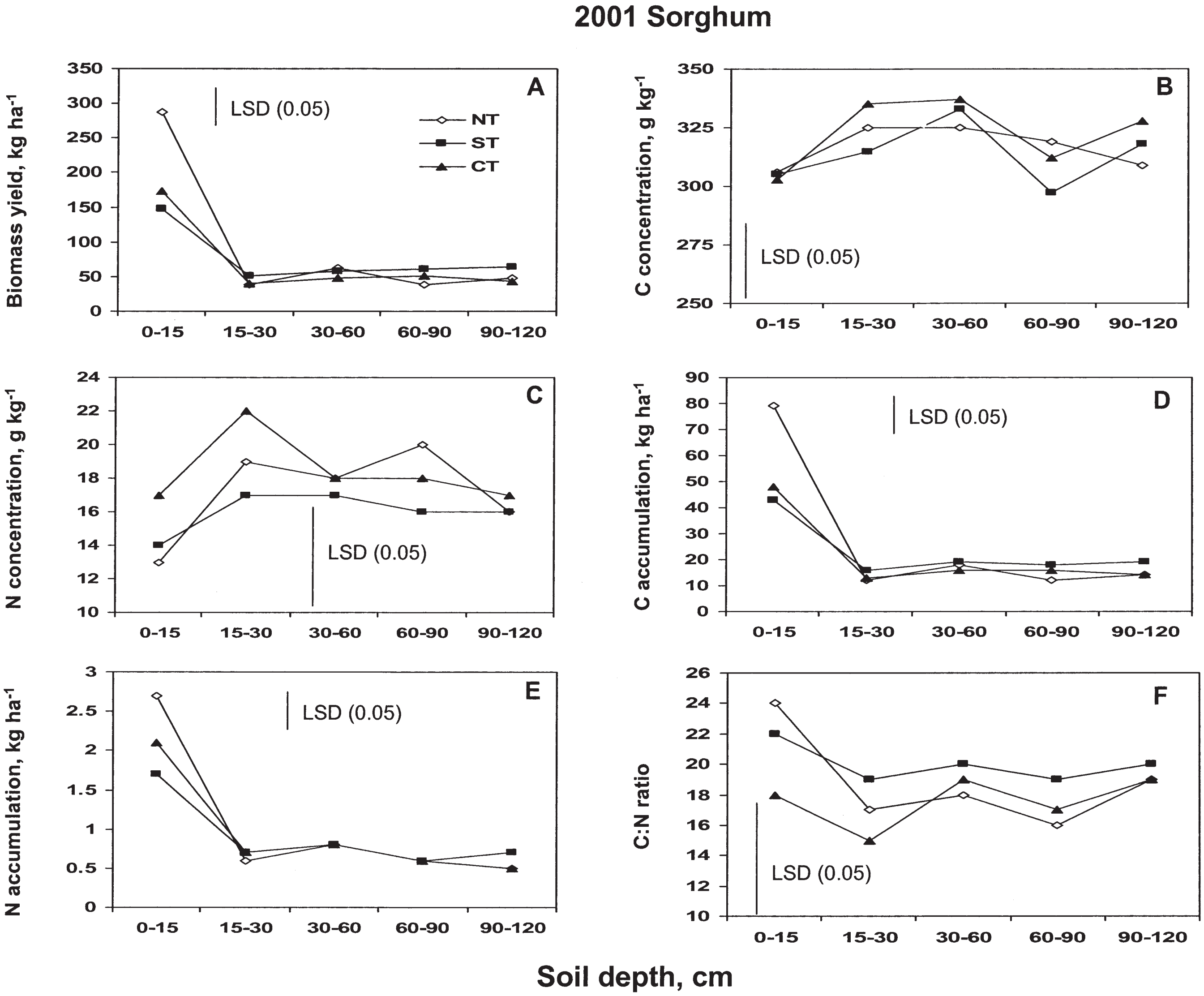


**Fig. 3. Effect of tillage on (A) biomass yield, (B) C concentration, (C) N concentration, (D) C accumulation, (E) N accumulation, and (F) C/N ratio of sorghum roots from the 0- to 120-cm depth in 2001. CT denotes chisel till; NT, no-till; and ST, strip-till. LSD(0.05) is the least significant difference between treatments at $P = 0.05$.**

extend to a depth of 1.8 to 1.9 m in the soil profile (Robertson et al., 1993; Stone et al., 2001).

Although tillage did not influence total root biomass yield and C and N accumulations at 0 to 120 cm in cotton and sorghum, it had variable effect with soil depth. Increased root biomass yield and C and N accumulations in 2000 cotton and 2001 sorghum in NT compared with ST and CT at 0 to 15 cm (Fig. 2 and 3) may have resulted from the mulch effect of accumulated crop residue at the soil surface, which may have conserved soil moisture and decreased soil temperature during summer, thereby promoting root growth (Baligar et al., 1996; Merrill et al., 1996; Rasse and Smucker, 1996). Stratification of nutrients, such as P (Holanda et al., 1998; Crozier et al., 1999), also could have resulted in increased root growth at the soil surface in NT than in ST and CT (Cannell and Hawes, 1994; Gregory, 1994). Soil compaction, which normally occurs in NT and restricts root growth, did not seem to occur in our study because bulk density was lower in NT and CT than in ST at 0 to 15 cm. In contrast, greater root biomass yield and C and N accumulations in 2000 cotton in ST than in NT and CT at 30 to 60 cm may have resulted from subsoiling in ST to a depth of 35 cm, which may have promoted root growth. Our results are consistent with those obtained by several researchers (Chan and Mead, 1992; Wulfsohn et al., 1996; Qin et al., 2004) who found greater root length density in wheat in NT than conventional till at 0 to 10 cm, but greater values in conventional till than in NT at 10 to 30 cm. However, some studies showed the opposite trend (Cornish, 1987) or no difference between NT and conventional till (Ehlers et al., 1983), probably due to differences in soil characteristics.

The time of application of tillage has also been shown to influence root growth of crops (Blevins and Frye, 1993; Qin et al., 2004), because soil properties change during the course of tillage implementation (Rhoton, 2000). Merrill et al. (1996) and Qin et al. (2004) reported

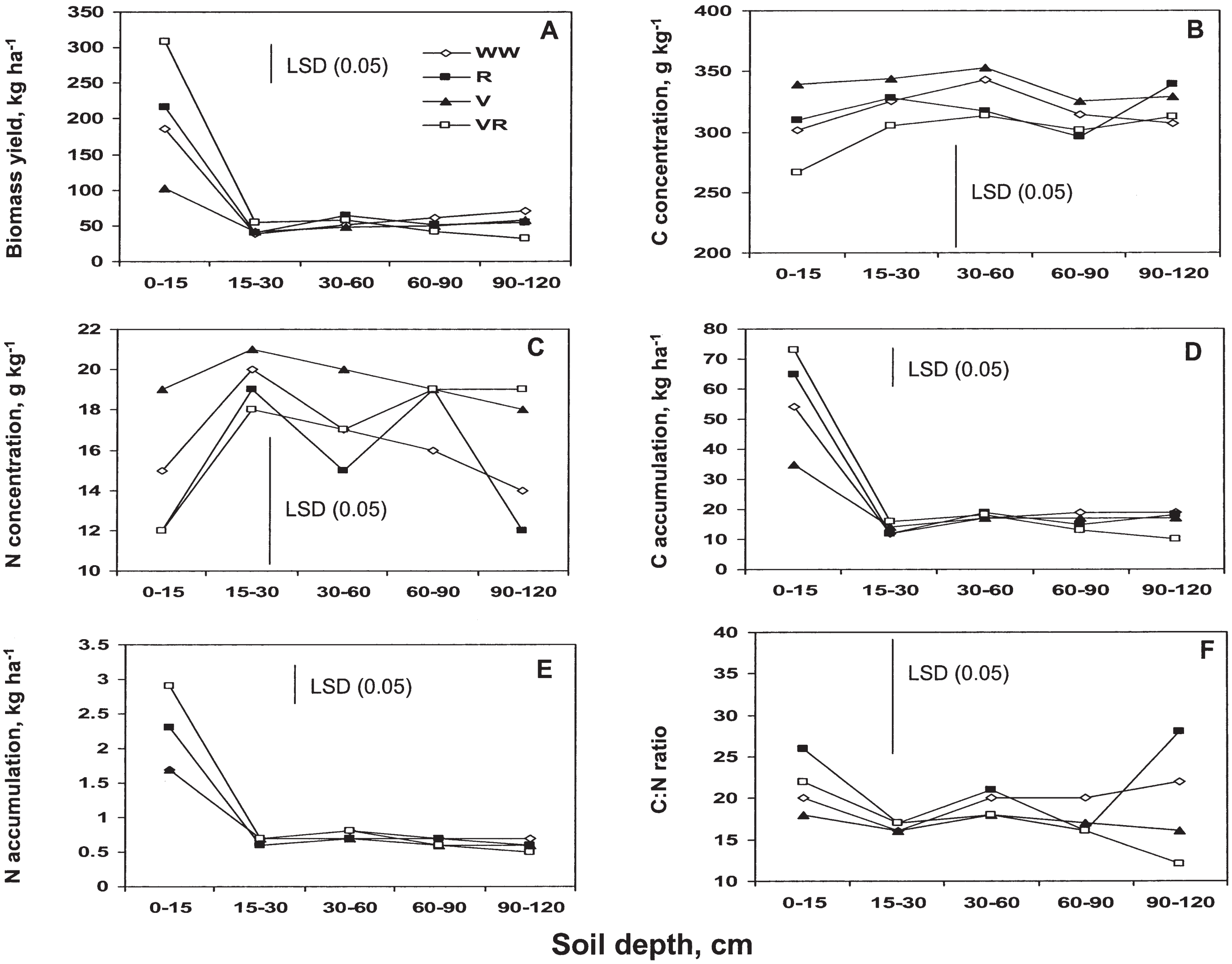


**Fig. 4. Effect of cover crops on (A) biomass yield, (B) C concentration, (C) N concentration, (D) C accumulation, (E) N accumulation, and (F) C/N ratio of sorghum roots from the 0- to 120-cm depth in 2001. R denotes rye; V, hairy vetch; VR, hairy vetch and rye biculture; and WW, winter weeds. LSD(0.05) is the least significant difference between treatments at $P = 0.05$.**

that the difference in root growth between NT and conventional tillage increased as the timing of tillage implementation increased. In our study, timing of tillage application seemed to have less influence on root growth because tillage × soil depth interaction was not significant for root biomass yield and C and N accumulations in 2002 cotton as they were for 2000 cotton and 2001 sorghum. Although the tillage treatment started in 1995, replacement of MT by ST in 2000 significantly increased soil bulk density at 0 to 15 cm compared with NT and CT (Table 10), but it had little effect on root biomass yield and C and N accumulations.

Cover crops have been shown to increase root growth and yield of the succeeding crops by increasing the number of biopores made by their roots, especially in compacted soil (Stirzaker and White, 1995; Rasse and Smucker, 1996; Williams and Weil, 2004). Although compaction does not seem to be a problem even in NT in our study, increased root biomass yield and C and N accumulations at 0- to 15-cm in 2001 sorghum with hairy vetch and rye biculture or rye compared with hairy vetch or winter weeds (Fig. 4) may have resulted from increased root growth of cover crops which increased the density of bipores, followed by increased N supply from their residues (Table 1). After removing cover crop roots and aboveground biomass from a small portion of some plots, we observed greater root biomass in biculture and rye than in hairy vetch and weeds. Increased root biomass yield and C and N accumulations or increased root length density in rye compared with hairy vetch or winter weeds have been observed elsewhere (Kuo et al., 1997a, 1997b; Sainju et al., 1998). Cover crops interacted with tillage in increasing total root biomass yield and C and N accumulations from 0- to 120-cm depth in NT or ST with cover crops compared with CT without cover crops (Tables 5, 7, and 8). Since NT improves soil structure resulting in extensive system of macropores (Ehlers et al., 1983; Martino and Shaykewich, 1994) and store more water in the soil profile than conventional tillage (Power et al., 1986; Nyborg and Malhi, 1989), cover crops may have improved root growth of cotton and sorghum in NT and ST by providing additional root channels

**Table 7. Effects of tillage and cover crops on total root biomass yield and C and N accumulations from the 0- to 120-cm soil depth averaged across N fertilization rates in 2001 sorghum.**

| Tillage† | Cover crop‡ | Total root biomass yield | Total C accumulation | Total N accumulation |
|---|---|---|---|---|
| | | kg ha$^{-1}$ | | |
| NT | WW | 455 | 138 | 3.6 |
| | R | 548 | 152 | 6.0 |
| | V | 165 | 56 | 3.4 |
| | VR | 538 | 126 | 5.0 |
| ST | WW | 344 | 98 | 4.1 |
| | R | 205 | 66 | 2.6 |
| | V | 332 | 117 | 4.2 |
| | VR | 405 | 108 | 3.6 |
| CT | WW | 218 | 69 | 3.6 |
| | R | 321 | 100 | 3.6 |
| | V | 228 | 75 | 3.4 |
| | VR | 461 | 120 | 5.8 |
| LSD(0.05) | | 320 | 78 | 2.4 |

† CT, chisel till; NT, no-till; and ST, strip till.
‡ R, rye; V, hairy vetch; VR, hairy vetch and rye biculture; and WW, winter weeds (no cover crops).

**Table 9. Effects of tillage and N fertilization rates on total root biomass yield and N accumulation from the 0- to 120-cm soil depth averaged across cover crops in 2002 cotton.**

| Tillage† | N fertilization | Total root biomass yield | Total N accumulation |
|---|---|---|---|
| | | kg ha$^{-1}$ | |
| NT | 0 | 487 | 3.3 |
| | 60 | 755 | 5.0 |
| | 120 | 787 | 5.3 |
| ST | 0 | 599 | 3.8 |
| | 60 | 824 | 5.9 |
| | 120 | 750 | 5.2 |
| CT | 0 | 637 | 5.1 |
| | 60 | 561 | 4.1 |
| | 120 | 518 | 4.1 |
| LSD(0.05) | | 301 | 1.8 |
| Means | 0 | 574a‡ | 4.0b |
| | 60 | 713a | 5.0a |
| | 120 | 685a | 4.9a |

† CT, chisel till; NT, no-till; and ST, strip till.
‡ Numbers followed by different letter with a column are significantly different at $P \leq 0.05$ by the least square means test.

along with existing macropore system where roots of cotton and sorghum can extend and efficiently utilize soil moisture and nutrients. Furthermore, legume cover crop shoots and roots may have provided additional N for cotton and sorghum roots, because both aboveground and belowground biomass of legume cover crops have higher N concentration than nonlegume or winter weeds (Kuo et al., 1997b). In undisturbed soil in NT, soil channels made by roots of previous crops were usually higher than in conventional till, where roots of present crop preferentially follow, resulting in a greater root growth in NT than in conventional till (Merrill et al., 1996).

Nitrogen fertilization can increase crop root growth by providing additional N (Weston and Zandstra, 1989; Garton and Widders, 1990, Sainju et al., 2001). Wilhelm et al. (1982) reported that wheat root growth was not influenced by N fertilization rates but fertilization with subtillage increased root growth. Similarly, Sainju et al. (2000) found that tomato root growth was higher in MT with 180 kg N ha$^{-1}$ than in NT with 0 kg N ha$^{-1}$ below the 26-cm depth. Although N fertilization did not increase root biomass yield and C and N accumulation in 2001 sorghum, increased root N accumulation in 2002 cotton with N fertilization (Table 9) may have resulted from increased N availability. Similarly, increased root biomass yield and C and N accumulations in ST or CT with 60 kg N ha$^{-1}$ in 2000 and 2002 cotton (Tables 6 and 8) suggests that tillage may have increased incorporation of N fertilizer to a greater depth, thereby increasing N availability and root growth. The 120 kg N ha$^{-1}$, however, did not increase root growth compared with 60 kg N ha$^{-1}$, suggesting that N fertilization rate can be reduced to reduce the cost of N fertilization and N leaching without decreasing cotton root biomass yield and C and N accumulations.

The C/N ratio of crop residue influences its rate of decomposition in the soil and N mineralization and availability (Frankenberger and Abdelmagid, 1985; Wagger et al., 1985). The C/N ratio in root biomass of cotton and sorghum was not influenced by tillage, cover crop, N fertilization, and their interactions at various soil depths (Table 3, Fig. 2–4). This suggests that even with increased N availability from legume cover crops and N fertilization or increased decomposition of root residue with increasing tillage intensity, cotton and sorghum roots probably accumulate or mineralize C and N from their residue in similar proportion.

A comparison of total root biomass yield and N accumulation at the 0- to 120-cm depth in 2000 and 2002 cotton revealed that root biomass yield and N accumu-

**Table 8. Effects of tillage and cover crops on total root biomass yield and N accumulation from the 0- to 120-cm soil depth averaged across N fertilization rates in 2002 cotton.**

| Tillage† | Cover crop‡ | Total root biomass yield | Total N accumulation |
|---|---|---|---|
| | | kg ha$^{-1}$ | |
| NT | WW | 650 | 3.4 |
| | R | 955 | 5.6 |
| | V | 689 | 4.9 |
| | VR | 410 | 3.8 |
| ST | WW | 824 | 5.7 |
| | R | 570 | 3.5 |
| | V | 802 | 5.5 |
| | VR | 700 | 5.1 |
| CT | WW | 588 | 4.3 |
| | R | 594 | 4.4 |
| | V | 504 | 4.1 |
| | VR | 602 | 4.9 |
| LSD(0.05) | | 452 | 1.8 |

† CT, chisel till; NT, no-till; and ST, strip till.
‡ R, rye; V, hairy vetch; VR, hairy vetch and rye biculture; and WW, winter weeds (no cover crops).

**Table 10. Soil bulk density as influenced by tillage and clay concentration in the soil measured after cotton harvest in November 2002.**

| Soil depth | Bulk density in tillage practices† | | | Clay content |
|---|---|---|---|---|
| | NT | ST | CT | |
| cm | Mg m$^{-3}$ | | | g kg$^{-1}$ |
| 0–15 | 1.41bC‡ | 1.51aB | 1.42bC | 100C |
| 15–30 | 1.54aB | 1.50aB | 1.54aB | 110C |
| 30–60 | 1.38aC | 1.42aC | 1.38aC | 250B |
| 60–90 | 1.61aA | 1.59aA | 1.57aAB | 280A |
| 90–120 | 1.61aA | 1.59aA | 1.60aA | 300A |

† CT, chisel till; NT, no-till; and ST, strip till.
‡ Bulk density values within a row followed by different lowercase letters and values within a column followed by uppercase letters are significantly different at $P \leq 0.05$ by the least square means test.

lation, averaged across treatments, were 97 to 104% greater in 2002 (853 and 12.6 kg ha$^{-1}$, respectively) than in 2000 (418 and 6.4 kg ha$^{-1}$). This could have resulted from higher temperature in September and October, followed by increased rainfall during the growing season from May to November in 2002 than in 2000 (Fig. 1A and 1B). Root growth can be influenced by temperature and moisture (Kuchenbuch and Barber, 1987; Stoffel et al., 1995; Merrill et al., 1996).

Although C input of 37 to 152 kg ha$^{-1}$ in cotton and sorghum roots were lower than 400 to 1400 kg ha$^{-1}$ reported in the literature (Qian and Doran, 1996; Kuo et al., 1997a), C from roots and those of as much as 580 kg ha$^{-1}$ accumulated in the rhizosphere (Helal and Sauerbeck, 1987) can substantially increase C level in the soil. Since the aboveground biomass is usually harvested, C and N inputs from roots and rhizosphere deposit form the sole source of soil organic matter. Conservation tillage, such as NT or ST, with hairy vetch and rye cover crop and 60 kg N ha$^{-1}$ can significantly increase root biomass yield and C and N accumulations in cotton and sorghum compared with CT with no cover crop and N fertilization, thereby helping to increase C and N sequestration in the soil and improving soil quality and productivity. Soil organic C and N levels are directly related with the amount of C and N inputs supplied by crop residue (Larson et al., 1972; Rasmussen et al., 1980).

## SUMMARY AND CONCLUSIONS

Since aboveground biomass of crops is generally harvested, roots become the sole source of C and N inputs for maintaining or increasing soil organic matter. There is a need to increase root biomass yield and C and N accumulations in crops using improved soil and management practices to recycle soil N to reduce N leaching, or sequester a greater amount of atmospheric C and N in the soil to help mitigate some of the deleterious effects of greenhouse gases and to improve soil quality and productivity. Carbon and N are not only added and/or recycled from crop roots, but a large amount of C is accumulated as rhizodeposit in the soil as well.

Root biomass yield and C and N accumulations in cotton and sorghum generally decreased with soil depth, except at 30 to 60 cm, where they increased due to reduced soil bulk density and high clay content. Tillage and cover crop did not directly influence root biomass and C and N accumulations but NT increased root biomass and C and N compared with ST and CT at the 0- to 15-cm depth in 2000 cotton and 2001 sorghum. In contrast, ST increased root biomass and C and N accumulations compared with NT and CT at 30 to 60 cm in 2000 cotton. Similarly, root biomass and C and N accumulations at 0 to 15 cm in 2001 sorghum were greater in hairy vetch and rye biculture and rye than in vetch or winter weeds. Tillage interacted with cover crop in increasing total root biomass and C and N accumulations from 0 to 120 cm in NT or ST with cover crops compared with CT without cover crop in 2000 cotton and 2001 sorghum. Similarly, total root biomass and C and N accumulations were greater in NT with 60 kg N ha$^{-1}$ than in CT with 0 kg N ha$^{-1}$ in 2000 and 2002 cotton. Conservation tillage, such as NT or ST, with hairy vetch and rye cover crops and 60 kg N ha$^{-1}$ can increase root biomass yield and C and N accumulations in cotton and sorghum compared with conventional tillage, such as CT, with no cover crop or N fertilization. As a result, this will help to maintain or increase soil organic matter and C and N sequestrations, thereby improving soil quality and sustaining crop productivity.

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