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Carbon Supply and Storage in Tilled and Nontilled Soils as Influenced by Cover Crops and Nitrogen Fertilization

Upendra M. Sainju,* Bharat P. Singh, Wayne F. Whitehead, and Shirley Wang

ABSTRACT

Soil carbon (C) sequestration in tilled and nontilled areas can be influenced by crop management practices due to differences in plant C inputs and their rate of mineralization. We examined the influence of 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 (or winter weeds)} and three nitrogen (N) fertilization rates (0, 60 to 65, and 120 to 130 kg N ha^{-1}) on C inputs from cover crops, cotton (*Gossypium hirsutum* L.), and sorghum [*Sorghum bicolor* (L.) Moench)], and soil organic carbon (SOC) at the 0- to 120-cm depth in tilled and nontilled areas. A field experiment was conducted on Dothan sandy loam (fine-loamy, siliceous, thermic Plinthic Paleudults) from 1999 to 2002 in central Georgia. Total C inputs to the soil from cover crops, cotton, and sorghum from 2000 to 2002 ranged from 6.8 to 22.8 Mg ha^{-1}. The SOC at 0 to 10 cm fluctuated with C input from October 1999 to November 2002 and was greater from cover crops than from weeds in no-tilled plots. In contrast, SOC values at 10 to 30 cm in no-tilled and at 0 to 60 cm in chisel-tilled plots were greater for biculture than for weeds. As a result, C at 0 to 30 cm was sequestered at rates of 267, 33, −133, and −967 kg C ha^{-1} yr^{-1} for biculture, rye, vetch, and weeds, respectively, in the no-tilled plot. In strip-tilled and chisel-tilled plots, SOC at 0 to 30 cm decreased at rates of 233 to 1233 kg C ha^{-1} yr^{-1}. The SOC at 0 to 30 cm increased more in cover crops with 120 to 130 kg N ha^{-1} yr^{-1} than in weeds with 0 kg N ha^{-1} yr^{-1}, regardless of tillage. In the subtropical humid region of the southeastern United States, cover crops and N fertilization can increase the amount of C input and storage in tilled and nontilled soils, and hairy vetch and rye biculture was more effective in sequestering C than monocultures or no cover crop.

Concerns for global warming have led to increased interests in sequestering atmospheric greenhouse gases, such as CO_2, in the terrestrial ecosystem (Dolman et al., 2003). Some of the ways to sequester atmospheric CO_2 in croplands are to use improved soil and crop management practices, such as conservation tillage, cover cropping, crop rotation, and N fertilization (Jastrow, 1996; Kuo et al., 1997a; Allmaras et al., 2000; Sainju et al., 2003). With these practices, C accumulated in the residue of above- and belowground biomass of crops after grain harvest is returned to the soil where a minimum amount of residue will be incorporated due to less soil disturbance. As a result, C storage in the soil increases due to increased C input and reduced mineralization compared to the conventional practices. Agricultural soils, being depleted of large amount of organic C due to cultivation, have significant potentials to sequester atmospheric CO_2 (Lal and Kimble, 1997; Paustian et al., 1997). Increased C sequestration can also enhance soil structure and improve soil water–nutrient–crop productivity relationships (Bauer and Black, 1994).

Cover cropping provides additional residue that not only reduces soil erosion but also improves soil productivity by increasing soil organic carbon (SOC) (McVay et al., 1989; Kuo et al., 1997a; Sainju et al., 2003). 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. Besides providing many benefits in improving soil physical, chemical, and biological properties (Doran, 1987; Smith et al., 1987; McVay et al., 1989; Roberson et al., 1991), some cover crops are also grown to supply N needs of the succeeding crops (Hargrove, 1986; Clark et al., 1994; Kuo et al., 1997b) and to reduce N leaching (Meisinger et al., 1990; McCracken et al., 1994). Similarly, N fertilization can increase SOC 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). Such management practices can provide opportunities to conserve SOC in the southeastern United States where organic matter level is generally lower than in the northern regions because of rapid mineralization (Doran, 1987; Doran and Smith, 1987).

Cover cropping and N fertilization can have variable effects in storing SOC in tilled and nontilled areas due to differences in mineralization rates of crop residues and soil organic matter. Conventional tillage enhances mineralization of SOC by incorporating crop residue, disrupting soil aggregates, and increasing aeration (Dalal and Mayer, 1986; Balesdent et al., 1990; Cambardella and Elliott, 1993), thereby reducing its level. In contrast, conservation tillage can increase C storage in the surface soil (Jastrow, 1996; Allmaras et al., 2000; Sainju et al., 2002). Studies suggest that conversion of conventional-till to no-till can sequester atmospheric CO_2 by 0.1% at the 0- to 5-cm soil depth every year, a total of 10 Mg in 25 to 30 yr (Lal and Kimble, 1997; Paustian et al., 1997). However, SOC below the 7.5-cm depth can be higher in tilled areas, depending on the soil texture, due to residue incorporation at greater depths (Jastrow, 1996; Clapp et al., 2000). The impact of tillage on SOC can interact 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

U.M. Sainju, USDA-ARS-NPARL, 1500 North Central Avenue, Sidney, MT 59270. B.P. Singh, W.F. Whitehead, and S. Wang, Agricultural Research Station, Fort Valley State University, Fort Valley, GA 31030. Received 12 May 2005. *Corresponding author (usainju@sidney.ars.usda.gov).

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Abbreviations: SOC, soil organic carbon.

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 moisture due to greater accumulation of crop residue at the soil surface than conventional tillage (Sandretto, 2001).

Little is known about the influence of cover cropping and N fertilization on crop biomass production, residue C input, and their relationships with soil C levels in tilled and nontilled areas. Conservation tillage can produce similar or higher cotton lint and sorghum grain yields and biomass production compared with conventional till (Torbert and Reeves, 1994; Bordovsky et al., 1998; Nyakatawa et al., 2000). Similarly, legume cover crops and N fertilization can increase cotton lint and sorghum grain yields and biomass production compared with nonlegume or no cover crops and N fertilization because of increased N supply (Touchton et al., 1984; Hargrove, 1986; Torbert and Reeves, 1994; Sainju et al., 2003). Carbon inputs can be added not only from aboveground but also from belowground biomass. Although aboveground biomass is mostly harvested, such as grains and lint for food and fiber, and stems and leaves (or straws, stalks) for animal feed (hay), litter, or fuel, belowground biomass, such as roots, forms the main source of soil organic C. As much as 7 to 43% of the total above- and belowground plant biomass C can be contributed by roots (Kuo et al., 1997a). Roots may play a dominant role in the soil C cycle (Wedin and Tilman, 1990; Gale et al., 2000; Puget and Drinkwater, 2001) and may have a relatively greater influence on SOC level 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 SOC than did stover. When C contributions from the rhizodeposition, such as root exudates, mucilages, and sloughed cells, and roots, were considered, corn root biomass contributed from 1.7 to 3.5 times more C to SOC than did stover (Allmaras et al., 2004; Wilts et al., 2004).

We hypothesized that cover cropping and N fertilization would increase SOC, regardless of tillage, due to greater amounts of C input returned to the soil compared with no cover cropping and N fertilization. Our objectives were to: (i) examine the amount of residue C supplied by above- and belowground biomass of cover crops, cotton, and sorghum as influenced by cover crop species and N fertilization in tilled and nontilled areas from 2000 to 2002, and (ii) determine the influence of cover crops and N fertilization rates on SOC in tilled and nontilled areas at the 0- to 120-cm depth in the subtropical humid region of 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 in 1999 at the Agricultural Research Station farm, Fort Valley State University, Fort Valley, GA. The areas with different tillage practices were established in 1995, before which these were tilled with disc harrow and chisel plows to a depth of 20 cm. In strip-tilled (or reduced-tilled) plots, cropping rows were subsoiled to 35 cm depth in a narrow strip of 30 cm width, thereby leaving areas between rows undisturbed. The surface-tilled zone is leveled by coulters 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 a 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, SOC at the 0- to 10-cm depth before the initiation of the experiment in October 1999 was 11.0 Mg C ha^{-1} in no-tilled, 10.6 Mg C ha^{-1} in strip-tilled, and 10.0 Mg C ha^{-1} in chisel-tilled plots. At 10 to 30 cm, SOC was 16.1 Mg C ha^{-1} in no-tilled, 16.0 Mg C ha^{-1} in strip-tilled, and 14.6 Mg C ha^{-1} in chisel-tilled plots. Previous crops from 1995 to 1999 were tomato (*Lycopersicum esculentum* Mill) and silage corn. 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), nonlegume (rye), legume and nonlegume (hairy vetch and rye) biculture, and winter weeds or no cover crop], and three N fertilization rates (0, 60 to 65, and 120 to 130 kg N ha^{-1}). The 120 kg N ha^{-1} rate 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 factor and N fertilization rate as the split-plot factor. Each experimental unit had three replications. The split-split plot size of an experimental unit was 7.2 × 7.2 m.

Cover Crop Management

Cover crops were planted in October–November, 1999 to 2001, in the same plot every year to examine their long-term influence on SOC. 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 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 based on the recommendation of Clark et al. (1994). Cover crops were drilled in 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 hand harvesting plant samples from two 1-m^2 areas randomly within each experimental unit and weighing in the field. After mixing the samples thoroughly, a subsample (approximately 100 g) was collected for determinations of dry matter yield and C concentration and the remainder of the plant samples was returned to the harvested area and spread uniformly by hand. In plots without cover crop, winter 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 were killed by spraying 3.36 kg ha^{-1} of glyphosate [*N*-(phosphonomethyl) glycine]. In chisel-tilled plots, cover crops 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, 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 the 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 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 on the soil surface in no-tilled, partly incorporated into the soil in strip-tilled, and completely incorporated in chisel-tilled plots by tillage operation. 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) at 8 kg ha^{-1} in 2000 and 2002 and sorghum (cv. 9212Y) at 12 kg ha^{-1} in 2001 was 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. Cotton was sprayed with glyphosate at 3.36 kg 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 ha^{-1} and metolachlor [(2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl) acetamide] at 1.3 kg 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 ha^{-1}. Cotton was also sprayed with a growth regulator, Pix (1,1-dimethylpiperdinium chloride), at 0.8 kg ha^{-1} at 2 mo after planting to control vegetative growth. Similarly, to defoliate leaves, cotton was sprayed with a defoliant, Cottonquik [1-aminomethanamide dihydrogen tetraoxosulfate ethephon (2-chloroethyl) phosphoric acid], at 2.8 L ha^{-1} a day after biomass collection and 2 to 3 wk before lint and seed harvest. Irrigation (25 mm rain using reel rain gun) was applied immediately after planting and fertilization and during dry periods to prevent moisture stress.

In October–November, 2000 and 2002, aboveground cotton biomass samples containing stems, leaves, and lint (including seeds) were hand harvested from two 1.8- × 1.8-m^2 areas randomly in places next to yield rows within the plot 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 C analysis. Lint yield was determined by hand harvesting lint containing seeds from two central rows (6.2 × 1.8 m^2), separating lint from seeds after ginning, and weighing them separately. Similarly, in November 2001, aboveground sorghum biomass containing stems and leaves (after removing grains) was collected from two 1.8- × 1.8-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 C analysis. Grain yield was determined by hand harvesting heads from two central rows (6.2 × 1.8 m^2), separating grains from heads, and weighing. After collecting samples, cotton lint containing seeds and sorghum grains was 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. Samples were collected from four holes, two in rows and two in between, in each plot, and 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 SOC, liners containing soil and root samples were cut into 0- to 10-, 10- to 30-, 30- to 60-, 60- to 90-, and 90- to 120-cm segments from the end containing topsoil and 50 g of root-free samples were collected from each segment to represent particular soil depths. Soil samples from four holes 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. For measuring bulk density, a separate undisturbed soil core (5-cm i.d.), divided into segments as above, was taken in November 2002, oven-dried at 105°C, and weighed.

Soil samples collected for determining root biomass were washed thoroughly with water in a nest of 1.0-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 the roots separated. Roots were oven-dried at 60°C for 3 d, weighed, ground, and passed through a 1-mm sieve for C determination.

Total C concentration (g C kg^{-1} plant dry weight) in above- (stems + leaves) and belowground biomass (roots) of cover crops, cotton, and sorghum was determined by using a C and N analyzer (LECO, St. Joseph, MI). Similarly, SOC concentration (g C kg^{-1} soil) in soil samples was determined by the C analyzer. Carbon content (Mg C ha^{-1}) in cover crop, cotton, and sorghum biomass was determined by multiplying dry matter weight by total C concentration. Similarly, SOC content in soil (Mg C ha^{-1}) at a particular depth was determined by multiplying SOC concentration by bulk density (for that depth and tillage treatment) and soil depth.

Data Analysis

Data for C content in above- and belowground biomass of cover crops, cotton, and sorghum for each sampling time, and SOC content in no-tilled, strip-tilled, and chisel-tilled systems were analyzed using the MIXED procedure of SAS after testing for homogeneity of variance (Littell et al., 1996). For analyzing data for plant biomass C, 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 in each tillage system and sampling time were considered as fixed effects, and replication and cover crop × replication interaction were considered as random effects. For SOC in each tillage system, cover crop was considered as main plot, N rate as split plot, soil depth as split-split plot, and time of sampling as split-split-split plot treatment for analysis. As a result, cover crop, N rate, soil depth, time of sampling, 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

Plant Biomass Carbon

Differences in C contents in above- and belowground biomass of cover crops, cotton, and sorghum due to treatments resulted in significant ($P \leq 0.05$) cover crop × N fertilization rate interaction in each tillage system and time of sampling. In no-tilled, strip-tilled, and chisel-tilled plots, C contents in above- and belowground biomass of cover crops were normally greater in hairy vetch and rye biculture than in monocultures or winter weeds from 2000 to 2002, regardless of N rates (Table 1). Carbon contents in aboveground biomass of cotton and sorghum were usually greater in vetch and biculture with or without N rates than in other treatments, except in rye and winter weeds with 120 to 130 kg N ha^{-1}. Carbon

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

		2000§				2001§				2002§				
		April		November		April		November		April		November		
Cover crop†	N rate‡	A¶	B¶	A	B	A	B	A	B	A	B	A	B	Total
	kg N ha^{-1}	Mg residue C ha^{-1}												
		No-tilled system												
Weeds	0	0.52	0.03	1.98	0.06	0.32	0.12	2.13	0.13	0.52	0.08	0.76	0.16	6.81
	60–65	0.52	0.03	2.78	0.15	0.22	0.15	1.96	0.18	0.20	0.05	1.37	0.21	7.82
	120–130	0.52	0.03	3.12	0.03	0.22	0.13	3.77	0.10	0.40	0.09	1.18	0.41	10.00
Rye	0	2.59	0.07	2.92	0.12	1.75	0.22	1.85	0.15	0.86	0.22	1.18	0.23	12.16
	60–65	2.59	0.07	4.06	0.08	1.77	0.18	1.97	0.14	1.00	0.15	1.21	0.52	13.74
	120–130	2.59	0.07	4.37	0.19	1.76	0.29	3.05	0.16	0.80	0.07	1.04	0.39	14.82
Vetch	0	2.12	0.06	4.57	0.05	0.85	0.14	4.17	0.05	2.11	0.06	2.07	0.19	16.44
	60–65	2.12	0.06	4.16	0.06	0.94	0.14	4.18	0.06	2.58	0.13	1.44	0.30	16.17
	120–130	2.12	0.06	5.10	0.08	0.86	0.13	4.14	0.05	1.53	0.11	1.27	0.33	15.75
Vetch–rye	0	3.28	0.15	3.64	0.17	2.08	0.24	3.33	0.17	2.42	0.09	1.97	0.19	17.73
	60–65	3.28	0.15	3.26	0.10	1.99	0.15	3.33	0.14	2.18	0.16	1.58	0.17	16.49
	120–130	3.28	0.15	4.90	0.02	2.24	0.22	3.94	0.07	2.41	0.12	1.46	0.13	18.94
LSD (0.05)		1.05	0.08	2.00	0.13	0.70	0.15	1.83	0.10	1.22	0.15	1.10	0.20	6.25
		Strip-tilled system												
Weeds	0	0.74	0.20	2.62	0.11	0.28	0.14	4.38	0.09	0.44	0.05	1.57	0.34	10.96
	60–65	0.74	0.20	3.38	0.72	0.29	0.27	5.71	0.08	0.63	0.03	1.83	0.34	14.22
	120–130	0.74	0.20	3.19	0.13	0.25	0.11	5.73	0.13	0.68	0.09	2.46	0.31	14.02
Rye	0	2.65	0.02	3.56	0.01	1.24	0.19	2.93	0.05	1.03	0.15	1.84	0.22	13.89
	60–65	2.65	0.02	4.18	0.01	1.55	0.14	4.15	0.08	1.27	0.10	2.20	0.24	16.59
	120–130	2.65	0.02	4.22	0.01	1.90	0.16	4.76	0.06	1.03	0.19	2.25	0.23	17.48
Vetch	0	1.39	0.06	3.58	0.17	0.62	0.23	6.28	0.09	1.41	0.05	1.85	0.13	15.81
	60–65	1.39	0.06	5.52	0.05	0.84	0.18	5.37	0.09	1.24	0.07	1.78	0.37	16.96
	120–130	1.39	0.06	6.31	0.23	0.69	0.27	4.33	0.17	1.59	0.09	1.97	0.46	17.56
Vetch–rye	0	3.34	0.28	4.23	0.08	2.23	0.29	6.33	0.14	1.19	0.17	1.67	0.27	20.22
	60–65	3.34	0.28	5.09	0.11	2.39	0.17	7.10	0.08	2.03	0.14	2.46	0.36	23.55
	120–130	3.34	0.28	4.99	0.10	3.29	0.19	6.26	0.10	1.57	0.10	1.93	0.20	22.35
LSD (0.05)		1.08	0.10	2.08	0.18	0.60	0.13	1.73	0.08	1.28	0.11	1.19	0.18	6.45
		Chisel-tilled system												
Weeds	0	0.33	0.05	3.01	0.03	0.17	0.10	5.09	0.07	0.32	0.04	2.54	0.24	11.99
	60–65	0.33	0.05	1.96	0.09	0.34	0.11	4.72	0.07	0.31	0.01	1.50	0.26	9.75
	120–130	0.33	0.05	4.21	0.05	0.19	0.10	6.61	0.07	0.34	0.03	1.61	0.21	13.79
Rye	0	2.15	0.07	2.20	0.18	1.30	0.22	3.42	0.09	0.59	0.17	0.90	0.32	11.61
	60–65	2.15	0.07	4.28	0.16	1.18	0.25	4.49	0.12	0.62	0.03	1.21	0.20	14.76
	120–130	2.15	0.07	3.38	0.06	1.61	0.23	5.43	0.09	0.79	0.05	2.05	0.19	16.09
Vetch	0	1.92	0.03	3.93	0.04	1.12	0.23	6.47	0.08	2.37	0.04	2.02	0.15	18.40
	60–65	1.92	0.03	4.02	0.25	0.83	0.12	6.44	0.08	1.68	0.04	1.62	0.23	11.26
	120–130	1.92	0.03	3.32	0.07	1.10	0.25	6.01	0.07	2.38	0.06	2.11	0.22	17.54
Vetch–rye	0	2.89	0.03	3.18	0.05	2.15	0.34	6.00	0.08	2.31	0.07	1.53	0.31	18.94
	60–65	2.89	0.03	4.50	0.07	2.53	0.28	6.18	0.15	2.31	0.13	2.73	0.21	22.01
	120–130	2.89	0.03	4.10	0.06	2.98	0.31	5.99	0.12	1.91	0.07	1.89	0.21	20.56
LSD (0.05)		1.07	0.10	2.14	0.15	0.69	0.69	1.88	0.10	1.20	0.16	1.06	0.26	6.50

† Cover crops are rye, cereal rye; vetch, hairy vetch; vetch–rye, hairy vetch and rye biculture; and weeds, winter weeds.
‡ 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.
§ Carbon from cover crop residues was 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 carbon; B, belowground biomass carbon.

contents in belowground biomass normally accounted for <15% of aboveground biomass. While C contents in aboveground biomass in 2002 cotton were lower than in 2000 cotton and 2001 sorghum, contents in belowground biomass were often higher. Total C content in above- and belowground biomass returned to no-tilled plots from 2000 to 2002 was greater in vetch and biculture with and without N rates and rye with N rates than in winter weeds with 0 and 60 to 65 kg N ha^{-1} (Table 1). In strip-tilled plots, total biomass C was greater in biculture with or without N rates than in winter weeds without N (Table 1). In chisel-tilled plots, total biomass C was greater in biculture with N rates than in winter weeds with or without N and in rye with 0 kg N ha^{-1} (Table 1). Because N fertilizer was applied to cotton and sorghum only after May 2000, C contents in above- and belowground biomass of cover crops in April 2000 were similar between N rates in tilled and nontilled plots.

The greater C content in above- and belowground biomass of vetch and rye biculture was due to higher biomass yield (5.7 to 8.2 Mg ha^{-1} aboveground, 372 to 880 kg ha^{-1} belowground) than in vetch (2.4 to 5.2 Mg ha^{-1} aboveground, 147 to 656 kg ha^{-1} belowground), rye (2.3 to 6.1 Mg ha^{-1} aboveground, 174 to 772 kg ha^{-1} belowground), and winter weeds (0.8 to 1.7 Mg ha^{-1} aboveground, 175 to 423 kg ha^{-1} belowground). Biomass yield of rye and C content decreased from 2000 to 2002, probably due to decreased availability of soil N, regardless of N rate and tillage. However, biomass yield and C content in vetch and biculture were consistent from 2000 to 2002, except for vetch in 2001, and were not affected by N rate and tillage. A lower temperature in December 2000 (Fig. 1A) could have reduced the growth and development of vetch and decreased its biomass yield and C content compared with that of rye in 2001.

The increased C content in aboveground biomass of cotton and sorghum in vetch and vetch and rye biculture with or without N rates compared with that in rye and weeds with 0 and 60 to 65 kg N ha^{-1} in tilled and nontilled plots was probably due to increased N supply by hairy vetch and its higher N concentration. Several researchers (Hargrove, 1986; McVay et al., 1989; Boquet et al., 2004) reported greater cotton lint and sorghum grain yields and biomass production with hairy vetch than with rye or no cover crop. Application of 120 to 130 kg N ha^{-1} with rye or weeds, however, increased C content in aboveground biomass of cotton and sorghum similar to those with vetch and biculture with or without N rates, indicating that adequate N is needed for biomass production when soil N is limited. Increased growing season rainfall from May to November in 2002 (719 mm) compared with that in 2000 (505 mm) (Fig. 1B) probably increased C content in belowground but not in aboveground biomass in cotton in 2002 compared with 2000. It could be possible that higher rainfall in September and October in 2002 than in 2000 (Fig. 1B) could have promoted belowground biomass of cotton better than aboveground biomass in 2002 due to limited time available for aboveground growth. It may also be possible that greater scavenging of N by sorghum in 2001 compared with those by crops in previous years reduced aboveground biomass growth in cotton in 2002 compared with 2000, thereby reducing C content. Total amounts of C returned to the soil from above- and belowground biomass of cover crops, cotton, and sorghum from 2000 to 2002 were comparable in tilled and nontilled plots, except for winter weeds. The amount of C contributed by cover crops varied between treatments and years, and ranged from 15% of the total C contributed by cover crops, cotton, and sorghum in weeds in no-tilled plots to 43% in biculture in strip-tilled plots.

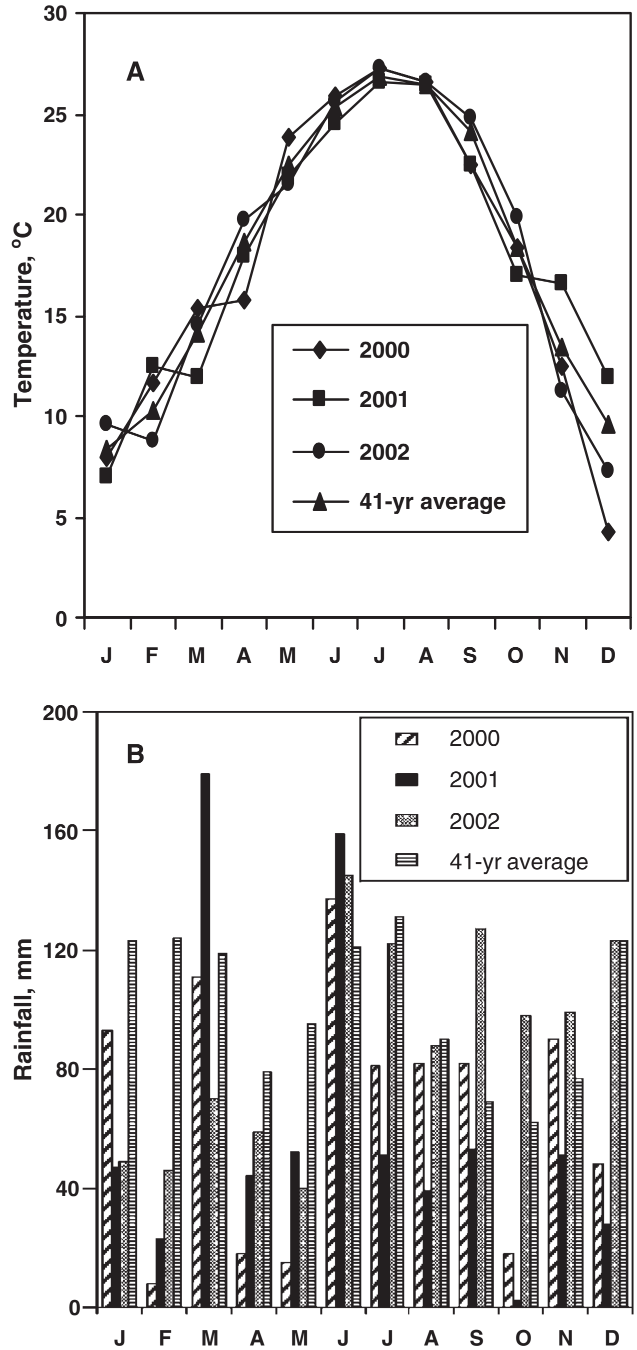

Fig. 1. (A) Mean monthly temperature and (B) total monthly rainfall from January to December in 2000, 2001, and 2002, and the 41-yr average near the experimental site.

Because weeds were controlled by applying herbicides in cotton and sorghum, the in-season weeds' contribution of C was considered minimal.

Soil Bulk Density

Bulk density in November 2002 was not influenced by cover crop and N fertilization rates but varied between tillage practices and soil depth. At the 0- to 10-cm depth, bulk density was significantly ($P \leq 0.05$) greater in strip-tilled than in no-tilled and chisel-tilled plots but was not different between tillage practices at other depths (Fig. 2). Bulk density values were higher at the 60- to 120-cm depth than at the 0- to 60-cm depth. For converting mass to volume basis of SOC, bulk density values at appropriate tillage system and soil depth were used.

Soil Organic Carbon

No-Tilled System

Differences in the effects of treatments and time of sampling at various soil depths resulted in significant ($P \leq 0.05$) cover crop × N rate × depth and cover crop × depth × time of soil sampling interactions on SOC in no-tilled plots (Table 2). The SOC at 0- to 10- and 10- to 30-cm depths, averaged across N rates, varied between cover crops from October 1999 to November 2002 (Fig. 3A and 3B). At 0 to 10 cm, SOC was significantly ($P \leq 0.05$) greater in hairy vetch than in winter weeds in April and November 2000, greater in rye than in weeds in April 2001, greater in vetch and rye than in biculture in November 2001, greater in hairy vetch than in rye, biculture, and weeds in April 2002, and greater in cover crops than in weeds in November 2002. At 10 to 30 cm, SOC was greater in biculture than in weeds in April 2000 and November 2002, and greater in rye and biculture than in weeds from April 2001 to April 2002. As a result, SOC fluctuated irregularly between cover crops at 0 to 10 cm but declined gradually from October 1999 to November 2002 in rye, vetch, and weeds at 10 to 30 cm.

Averaged across sampling times, SOC at 0 to 10 cm in the no-tilled system was greater in vetch with 0 kg N ha^{-1} than in weeds with 0 and 60 to 65 kg N ha^{-1} and in vetch and rye biculture with 0 kg N ha^{-1} (Table 3). At 10 to 30

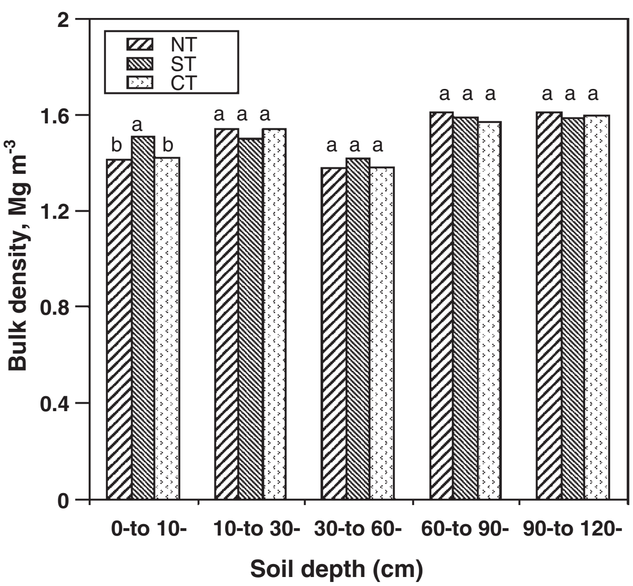

Fig. 2. Soil bulk density in tilled and nontilled systems at the 0- to 120-cm depth averaged across cover crops and N fertilization rates. CT, chisel-tilled system; NT, no-tilled system; ST, strip-tilled system. Bars followed by different letters within a depth are significantly different at $P \leq 0.05$ by the least square means test.

Table 2. Analysis of variance for soil organic C in no-tilled, strip-tilled, and chisel-tilled systems.

Source	No-till	Strip-till	Chisel-till
Cover crop (C)	NS†	NS	NS
N fertilization (F)	‡	NS	‡
C × F	NS	NS	‡
Soil depth (D)	***	***	***
C × D	NS	‡	*
F × D	NS	NS	**
C × F × D	***	*	*
Time of sampling (T)	**	NS	**
C × T	*	NS	**
F × T	NS	NS	NS
C × F × T	NS	NS	NS
D × T	NS	NS	NS
C × D × T	***	NS	***
F × D × T	NS	NS	NS
C × F × D × T	NS	NS	NS

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Not significant.
‡ Significant at the 0.1 probability level.

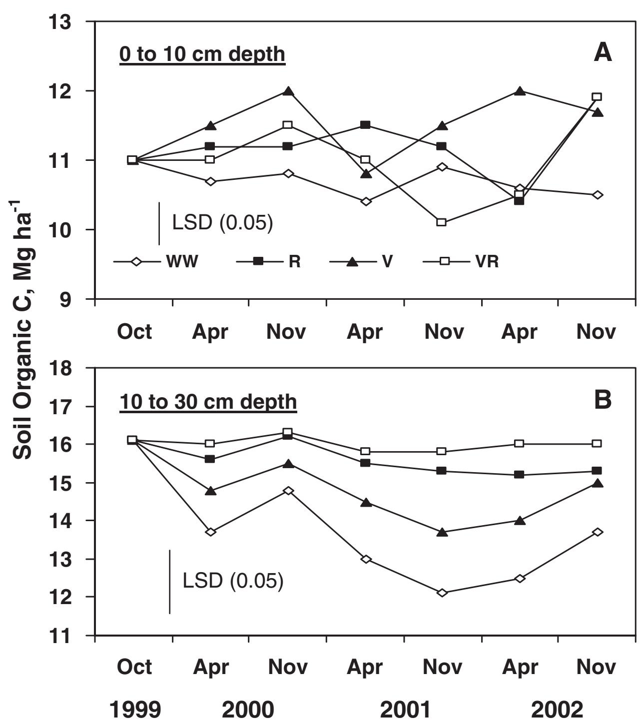

Fig. 3. Effects of cover crops on soil organic C in a no-tilled system from October 1999 to November 2000 at the (A) 0- to 10- and (B) 10- to 30-cm depths averaged across N fertilization rates. R, cereal rye; V, hairy vetch; VR, hairy vetch and rye biculture; WW, winter weeds. LSD (0.05) is the least significant difference between cover crops within a sampling date at $P \leq 0.05$.

cm, SOC was greater in rye with 120 to 130 kg N ha^{-1} than in weeds with or without N rates, rye with 0 kg N ha^{-1}, and vetch with 0 and 120 to 130 kg N ha^{-1}. The SOC at 30 to 120 cm was not influenced by treatments and sampling dates.

The variations in SOC at the 0- to 10- and 10- to 30-cm depths between cover crops from October 1999 to November 2002 (Fig. 3) could be due to differences in the amount of residue C returned to the soil from above- and belowground biomass of cover crops, cotton, and sorghum (Table 1). As the amount of residue C returned to the soil increased, SOC also increased. For example, higher SOC at 0 to 10 cm in vetch than in weeds in April and November 2000 and April 2002 (Fig. 3A) could be due to a greater amount of residue C returned to the soil from cotton and sorghum biomass with vetch treatment in November 2000 and 2001 and from vetch biomass in April 2000 and 2002 (Table 1). A direct relationship exists between C input rates and SOC, regardless of tillage practices (Larson et al., 1972; Lal et al., 1980; Rasmussen et al., 1980). At 10 to 30 cm, variations in SOC between cover crops from October 1999 to November 2002 could be due to differences in C inputs, primarily from belowground biomass of cover crops, cotton, and sorghum. The higher SOC at 10 to 30 cm in rye and biculture than in vetch and weeds in April 2000 and from April 2001 to November 2002 (Fig. 3B) could be due to a greater amount of C returned to the soil from belowground biomass of rye and biculture, followed by those from belowground biomass of cotton and sorghum with these cover crops (Table 1). As a result, the rate of decline of SOC at 10 to 30 cm from October 1999 to November 2002 was more gradual with rye and biculture than with vetch and weeds. Rye has been known to produce more belowground biomass than hairy vetch (Shipley et al., 1992; Kuo et al., 1997a, 1997b). Root-derived C is retained longer and forms a major proportion of SOC that is responsible for soil structural improvement than shoot-derived C in no-tilled systems (Gale and Cambardella, 2000; Puget and Drinkwater, 2001). The nonsignificant effects of cover crops and N fertilization on SOC at the 30- to 120-cm depth probably resulted from the limited amount of C inputs from belowground biomass of cover crops, cotton, and sorghum, because a large percentage of these crops' root growth occurs in the surface soil (Bedford and Henderson, 1985; Box and Ramseur, 1993; Sainju et al., 1998).

Table 3. Effects of cover crops and N fertilization rates on soil organic carbon (SOC) in the no-tilled, strip-tilled, and chisel-tilled systems at the 0- to 120-cm depth averaged across sampling times.

Cover crop†	N rate‡	SOC at various depths (cm) 0–10	10–30	30–60	60–90	90–120
	kg N ha^{-1}	Mg soil C ha^{-1}				
				No-tilled system		
Weeds	0	10.6	14.0	10.1	8.4	7.0
	60–65	10.6	13.8	11.7	9.4	6.4
	120–130	10.9	13.3	10.5	7.0	5.6
Rye	0	11.1	14.1	10.3	7.9	5.3
	60–65	11.1	15.6	10.3	8.1	5.8
	120–130	11.5	17.1	11.3	6.6	6.8
Vetch	0	11.8	14.4	11.7	9.3	6.0
	60–65	11.2	16.1	12.9	8.1	6.3
	120–130	11.5	14.0	11.9	8.8	6.2
Vetch–rye	0	10.6	15.5	11.5	9.0	6.7
	60–65	10.9	16.0	10.7	7.3	5.7
	120–130	11.6	16.5	11.0	6.7	5.7
LSD (0.05)		1.0	2.3	3.4	3.4	2.2
				Strip-tilled system		
Weeds	0	9.7	13.7	9.9	6.9	6.1
	60–65	8.8	14.0	10.1	8.0	5.6
	120–130	10.2	15.5	9.4	8.3	5.6
Rye	0	9.4	14.3	8.8	6.7	5.2
	60–65	9.7	15.3	10.8	7.9	5.8
	120–130	11.0	16.7	10.3	6.4	5.4
Vetch	0	10.0	14.3	9.7	6.5	5.8
	60–65	9.9	14.5	9.2	6.5	5.7
	120–130	10.3	15.9	9.0	6.4	5.5
Vetch–rye	0	9.0	14.7	10.1	8.4	4.9
	60–65	9.1	14.9	10.6	7.3	5.4
	120–130	10.8	15.1	10.3	7.9	6.6
LSD (0.05)		1.0	2.8	3.0	3.3	2.1
				Chisel-tilled system		
Weeds	0	8.0	12.4	9.2	7.1	5.5
	60–65	9.2	13.1	9.8	6.7	4.5
	120–130	9.4	13.1	9.4	7.9	6.2
Rye	0	8.9	12.9	8.8	7.6	6.0
	60–65	9.0	13.7	9.1	7.1	5.8
	120–130	9.1	14.0	12.1	8.1	5.9
Vetch	0	9.1	13.9	10.9	6.4	6.0
	60–65	9.1	13.6	10.3	7.0	6.0
	120–130	9.5	14.6	12.1	8.0	6.6
Vetch–rye	0	9.5	14.3	10.4	8.1	6.4
	60–65	10.1	14.2	11.0	8.3	5.0
	120–130	9.5	14.6	11.0	7.8	6.0
LSD (0.05)		0.9	2.2	2.9	3.4	2.3

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

Nitrogen fertilization interacted more with nonlegume than with legume cover crop in increasing SOC, because 120 to 130 kg N ha^{-1} increased SOC at 10 to 30 cm with rye and at 0 to 10 cm with biculture more than 0 kg N ha^{-1} (Table 3). Rye and succeeding cotton and sorghum may respond favorably to N fertilization, thereby increasing the amount of residue C in above- and belowground biomass returned to the soil (Table 1). Nitrogen fertilization has been known to increase SOC due to increased biomass residue returned to the soil (Liang and Mackenzie, 1992; Gregorich et al., 1996; Omay et al., 1997). In contrast, N fertilization did not seem to influence biomass growth of vetch because C content in vetch was similar between N fertilized and unfertilized treatments (Table 1), thereby having little influence on SOC (Table 3).

Strip-Tilled System

Cover crop, time of soil sampling, and their interaction did not influence SOC in strip-tilled plots. In contrast, cover crop × N fertilization × soil depth interaction was significant ($P \leq 0.05$) (Table 2). The SOC at the 0- to 10-cm depth, averaged across sampling times, was significantly ($P \leq 0.05$) greater with 120 to 130 than with 60 to 65 kg N ha^{-1} in weeds, and greater with 120 to 130 than with 0 or 60 to 65 kg N ha^{-1} in rye and vetch and rye biculture (Table 3). The SOC was also greater in rye with 120 to 130 kg N ha^{-1} than in rye, vetch, biculture, and weeds with 0 and 60 kg N ha^{-1}. At 10 to 30 cm, SOC was greater in rye with 120 to 130 kg N ha^{-1} than in weeds with 0 kg N ha^{-1}. At 30 to 120 cm, SOC was not influenced by treatments.

The lack of significant difference in SOC between cover crops and time of sampling in strip-tilled plots may have resulted from the difference in the incorporation of residues into the soil in tilled and nontilled rows. Residues were incorporated to a greater depth in tilled rows but were left at the soil surface in nontilled rows. Since soil samples were collected both from tilled and nontilled rows and were composited by depth, the differences in SOC between cover crops and time of sampling could have diminished due to mixing of residues and soils from tilled and nontilled areas. However, adequate amount of N fertilization clearly increased SOC at 0 to 10 cm in rye, biculture, and weeds, since amount of residue C returned to the soil from above- and belowground biomass also increased with N fertilization in these cover crops (Table 1). As in no-tilled plots, rye seemed to be more effective in increasing SOC at the 0- to 10- and 10- to 30-cm depths with 120 to 130 kg N ha^{-1} than other cover crops, probably due to the increased amount of residue C returned to the soil from above- and belowground biomass and those from succeeding cotton and sorghum.

Chisel-Tilled System

As in no-tilled plots, cover crop × N fertilization × soil depth and cover crop × depth × time of soil sampling interactions were significant ($P \leq 0.05$) for SOC in chisel-tilled plots (Table 2). The SOC, however, did not vary with differences in the amount of residue C returned to the soil from cover crops at various sampling times, as it did in no-tilled plots. The SOC at the 0- to 60-cm depth declined gradually from October 1999 to November 2002 in chisel-tilled plots (Fig. 4). The rate of decline varied with cover crop species. As a result, SOC at 0 to 10 cm, averaged across N rates, was significantly ($P \leq 0.05$) greater in vetch and rye biculture than in weeds in April 2000; than in vetch, rye, and weeds in April 2001; and than in rye and weeds in April 2002 (Fig. 4A). The SOC was also greater in vetch and biculture than in weeds in November 2002. At 10 to 30 cm, SOC was greater in biculture than in weeds in April and November 2000 and April 2001, and greater in biculture than in rye and weeds in November 2001 and April 2002 (Fig. 4B). At 30 to 60 cm, SOC was greater in vetch and biculture than in weeds in April 2000 and 2001, and than in rye and weeds from November 2001 to November 2002 (Fig. 4C).

Averaged across sampling times, SOC at the 0- to 10-cm depth was greater in biculture with 60 to 65 kg N ha^{-1} than in vetch and weeds with 0 and 60 to 65 kg N ha^{-1} and in rye with and without N rates (Table 3). At 10 to 30 cm, SOC was greater in vetch and biculture with 120 to 130 kg N ha^{-1} than in weeds with 0 kg N ha^{-1}. At 30 to 60 cm, SOC was greater in rye and vetch with 120 to 130 kg N ha^{-1} than in weeds with 0 kg N ha^{-1} and in rye with 0 and 60 to 65 kg N ha^{-1}. At 60 to 120 cm, SOC was not influenced by treatments and sampling times.

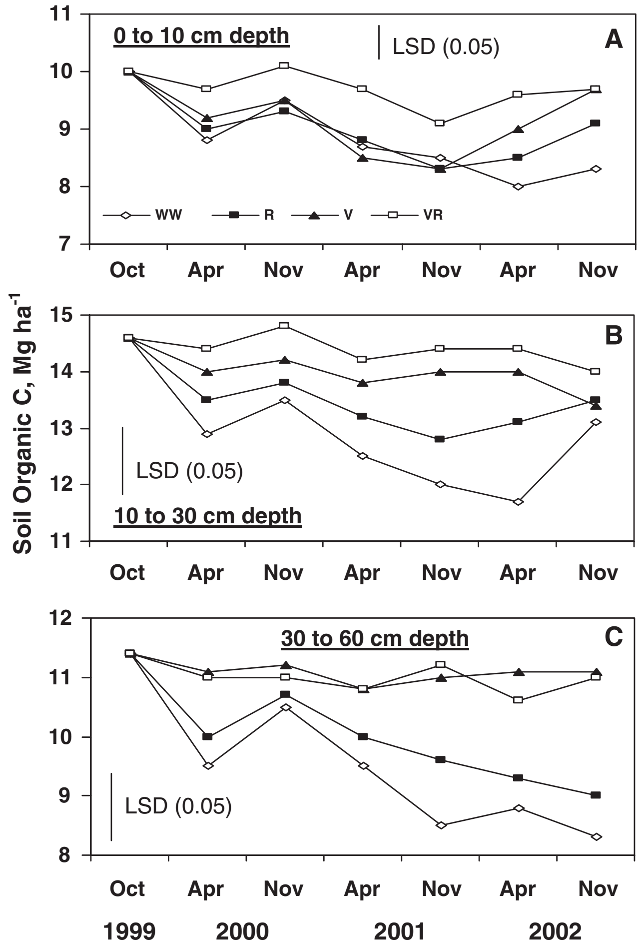

Fig. 4. Effects of cover crops on soil organic C in a chisel-tilled system from October 1999 to November 2000 at the (A) 0- to 10-, (B) 10- to 30-, and (C) 30- to 60-cm depths averaged across N fertilization rates. R, cereal rye; V, hairy vetch; VR, hairy vetch and rye biculture; WW, winter weeds. LSD (0.05) is the least significant difference between cover crops within a sampling date at $P \leq 0.05$.

Addition of various rates of residue C at different times of the year did not sharply affect SOC levels in chisel-tilled soil (Fig. 4), as they did in no-tilled soil, especially at the 0- to 10-cm depth. Increased amounts of residue C with cover crops, however, reduced the rate of decline of SOC at the 0- to 60-cm depth from October 1999 to November 2002 compared with winter weeds. Incorporation of residue to a greater depth in chisel-tilled plots likely reduced the fluctuation in SOC levels. Residue C, both from above- and belowground biomass, was incorporated into the soil during tillage. As a result, SOC levels varied with cover crops and time of sampling at the 0- to 60-cm depth, unlike in no-tilled and strip-tilled plots where the variations were limited only at the 0- to 30-cm depth. Although all cover crops were effective in reducing the SOC level compared with winter weeds, vetch and rye biculture maintained the highest level at the 0- to 60-cm depth from October 1999 to November 2002, probably due to a greater amount of residue C returned to the soil (Table 1). Kuo et al. (1997a) reported that rye increased SOC at the 0- to 30-cm depth compared with hairy vetch or winter weeds

Table 4. Soil C sequestration in tilled and nontilled systems as influenced by cover crops averaged across N fertilization rates from October 1999 to November 2002.

Tillage	Cover crop†	Changes in soil organic C from October 1999 to November 2002 at various depths (cm)			C sequestration rate at various depths (cm)			Amount of plant residue C converted to soil organic C at various depths (cm)		
		0–10	10–30	0–30	0–10	10–30	0–30	0–10	10–30	0–30
		Mg soil C ha^{-1}			kg C ha^{-1} yr^{-1}			g kg^{-1}		
No-till	weeds	−0.5 (−5)‡	−2.4 (−15)	−2.9 (−11)	−167	−800	−967	−60	−290	−350
	rye	0.9 (8)	−0.8 (−5)	0.1 (0.4)	300	−267	33	80	−70	10
	vetch	0.7 (6)	−1.1 (−7)	−0.4 (−1)	233	−367	−133	40	−70	−20
	vetch–rye	0.9 (8)	−0.1 (−1)	0.8 (3)	300	−33	267	50	−10	40
Strip-till	weeds	−1.0 (−9)	−2.7 (−17)	−3.7 (−14)	−333	−900	−1233	−80	−210	−290
	rye	−0.6 (−6)	−1.6 (−10)	−2.2 (−8)	−200	−533	−733	−40	−100	−140
	vetch	−0.9 (−8)	−1.8 (−11)	−2.7 (−10)	−300	−600	−900	−50	−110	−160
	vetch–rye	−0.3 (−3)	−1.1 (−7)	−1.4 (−5)	−100	−367	−467	−10	−50	−60
Chisel-till	weeds	−1.7 (−17)	−1.5 (−10)	−3.2 (−13)	−567	−500	−1066	−140	−130	−270
	rye	−0.9 (−9)	−1.1 (−8)	−2.0 (−8)	−300	−367	−667	−60	−80	−140
	vetch	−0.3 (−3)	−1.2 (−8)	−1.5 (−6)	−100	−400	−500	−20	−80	−100
	vetch–rye	−0.3 (−3)	−0.6 (−4)	−0.7 (−3)	−100	−200	−233	−10	−30	−40

† Cover crops are rye, cereal rye; vetch, hairy vetch; vetch–rye, hairy vetch and rye biculture; and weeds, winter weeds.
‡ Numbers in parentheses are % change in soil organic C.

due to an increased amount of residue C returned to the conventional-tilled system.

Nitrogen fertilization increased SOC at the 0- to 60-cm depth in cover crops and winter weeds (Table 3). Unlike in no-tilled and strip-tilled plots where the effect of N fertilization in increasing SOC was pronounced with weeds, rye, and biculture treatments, N fertilization also increased SOC with hairy vetch in surface and subsurface soils when chisel-tilled. Increased residue C resulting from increased N supplied by both N fertilization and vetch (Table 1) probably were more effective in increasing SOC when residues were incorporated to a greater depth in chisel-tilled soils.

Changes in Soil Organic Carbon

Differences in the amount of residue C returned to the soil between cover crops and their rate of mineralization due to tillage caused changes in SOC levels increased or decreased from October 1999 to November 2002 (Table 4). In no-tilled plots, SOC decreased by 5 to 15% with winter weeds at the 0- to 10-, 10- to 30-, and 0- to 30-cm depths. In contrast, SOC increased by 6 to 8% with cover crops at 0 to 10 cm and by 0.4% with rye and 3% with vetch and rye biculture at 0 to 30 cm. As a result, SOC at 0 to 10 cm was sequestered at a rate of 233 to 300 kg C ha^{-1} yr^{-1} with cover crops but was lost at a rate of 167 kg C ha^{-1} yr^{-1} without cover crops. At 10 to 30 cm, C was lost from the soil regardless of cover crop species; however, the rate of loss decreased with increases in residue C returned to the soil from cover crops (Table 1). At 0 to 30 cm, SOC was sequestered at the rates of 33 kg C ha^{-1} yr^{-1} with rye and 267 kg C ha^{-1} yr^{-1} with biculture. West and Post (2002) concluded that enhanced crop rotation can sequester 200 ± 120 kg C ha^{-1} yr^{-1}, reaching equilibrium in 40 to 60 yr, due to an increased amount of crop residue returned to the soil. The amount of plant residue C converted into SOC at 0 to 10 cm as a result of sequestration varied from 4% in vetch to 8% in rye. At 0 to 30 cm, the conversion was 1% in rye and 4% in biculture.

In strip-tilled and chisel-tilled plots, SOC decreased by 3 to 17% at 0 to 10 cm, 4 to 17% at 10 to 30 cm, and 3 to 14% at 0 to 30 cm from October 1999 to November 2002, regardless of cover crop species (Table 4). The percent decrease, however, was lower in cover crops than in weeds. While the percent decrease was similar between rye and vetch, it was lower in the biculture. As a result, the SOC loss ranged from 100 to 567 kg C ha^{-1} yr^{-1} at 0 to 10 cm, from 200 to 900 kg C ha^{-1} yr^{-1} at 10 to 30 cm, and from 233 to 1233 kg C ha^{-1} yr^{-1} at 0 to 30 cm.

Because of increased C storage in no-tilled and reduced C loss in strip-tilled and chisel-tilled plots, hairy vetch and rye biculture can be used to sequester C in a no-till system or replace C lost by mineralization in a tilled system better than hairy vetch or rye alone, or no cover crops. Higher amounts of residue C returned to

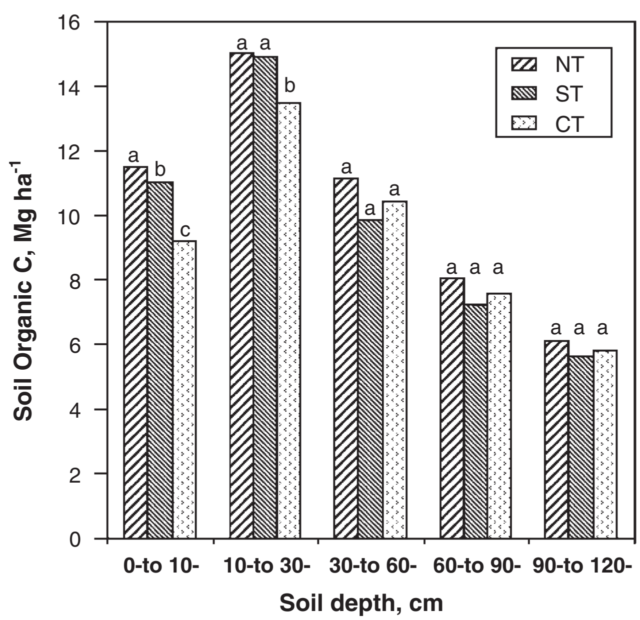

Fig. 5. Soil organic C in tilled and nontilled systems at the 0- to 120-cm depth averaged across cover crops and N fertilization rates. CT, chisel-tilled system; NT, no-tilled system; ST, strip-tilled system. Bars followed by different letters within a depth are significantly different at $P \leq 0.05$ by the least square means test.

the soil both from above- and belowground biomass (Table 1) probably conserved C in tilled and nontilled systems in biculture better than in monocultures or no cover crops. Since it takes a long time to stabilize C in the soil from crop residues, longer periods of time than the present 3 yr of study may be needed to examine C dynamics and sequestration in tilled and nontilled fields as influenced by cover crops and N fertilization.

As a result of differences in C addition from above- and belowground biomass of cover crops, cotton, and sorghum and their mineralization rates, SOC in November 2002 was still lower in chisel-tilled than in no-tilled and strip-tilled plots at the 0- to 10- and 10- to 30-cm depths (Fig. 5). The SOC in strip-tilled plot was lower than in no-tilled plot at 0 to 10 cm but was similar at 10 to 30 cm. Increased residue returned to the soil will probably increase C storage in a strip-tilled system to a level similar to that in a no-tilled system within a short period, but it may take a lot of residue and a long time for the SOC level in a chisel-tilled system to be equal to that in a no-tilled system.

CONCLUSIONS

Results of this study revealed that cover crops and N fertilization can increase the amount of residue C returned to the soil from above- and belowground biomass and SOC compared with no cover crop and N fertilization in tilled and nontilled systems. Residue amount and type influenced SOC level at the surface layer in the no-tilled system but higher residue C reduced the rate of decline of SOC in subsurface layer in no-tilled and surface and subsurface layers in tilled systems from October 1999 to November 2002. The SOC increased in cover crops with 120 to 130 kg N ha^{-1} compared with no cover crops and N fertilization, regardless of tillage. A greater amount of residue returned from hairy vetch and rye biculture and succeeding cotton and sorghum increased SOC in the no-tilled system or reduced its loss in the tilled system compared with those from monocultures or no cover crops. Residue management, such as residue removal vs. returned to the soil, can have a significant impact on storing C in the soil, regardless of tillage, since C input from residue is directly related to SOC content. The benefits of increasing C sequestration include not only improving soil quality and crop productivity, but also reducing greenhouse gas levels in the atmosphere. A C credit should be used to encourage producers to adapt soil and crop management practices for increasing C sequestration in the soil.

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