ELSEVIER

Soil & Tillage Research 63 (2002) 167–179

Soil & Tillage Research

www.elsevier.com/locate/still

Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA

U.M. Sainju*, B.P. Singh, W.F. Whitehead

Agricultural Research Station, Fort Valley State University, 1005 State University Drive, Fort Valley, GA 31030, USA

Received 15 November 2000; received in revised form 7 August 2001; accepted 16 August 2001

Abstract

Maintaining and/or conserving organic carbon (C) and nitrogen (N) concentrations in the soil using management practices can improve its fertility and productivity and help to reduce global warming by sequestration of atmospheric CO_2 and N_2. We examined the influence of 6 years of tillage (no-till, NT; chisel plowing, CP; and moldboard plowing, MP), cover crop (hairy vetch (*Vicia villosa* Roth.) vs. winter weeds), and N fertilization (0, 90, and 180 kg N ha^{-1}) on soil organic C and N concentrations in a Norfolk sandy loam (fine-loamy, siliceous, thermic, Typic Kandiudults) under tomato (*Lycopersicon esculentum* Mill.) and silage corn (*Zea mays* L.). In a second experiment, we compared the effects of 7 years of non-legume (rye (*Secale cereale* L.)) and legume (hairy vetch and crimson clover (*Trifolium incarnatum* L.)) cover crops and N fertilization (HN (90 kg N ha^{-1} for tomato and 80 kg N ha^{-1} for eggplant)) and FN (180 kg N ha^{-1} for tomato and 160 kg N ha^{-1} for eggplant)) on soil organic C and N in a Greenville fine sandy loam (fine-loamy, kaolinitic, thermic, Rhodic Kandiudults) under tomato and eggplant (*Solanum melogena* L.). Both experiments were conducted from 1994 to 2000 in Fort Valley, GA. Carbon concentration in cover crops ranged from 704 kg ha^{-1} in hairy vetch to 3704 kg ha^{-1} in rye in 1999 and N concentration ranged from 77 kg ha^{-1} in rye in 1996 to 299 kg ha^{-1} in crimson clover in 1997. With or without N fertilization, concentrations of soil organic C and N were greater in NT with hairy vetch than in MP with or without hairy vetch (23.5–24.9 vs. 19.9–21.4 Mg ha^{-1} and 1.92–2.05 vs. 1.58–1.76 Mg ha^{-1}, respectively). Concentrations of organic C and N were also greater with rye, hairy vetch, crimson clover, and FN than with the control without a cover crop or N fertilization (17.5–18.4 vs. 16.5 Mg ha^{-1} and 1.33–1.43 vs. 1.31 Mg ha^{-1}, respectively). From 1994 to 1999, concentrations of soil organic C and N decreased by 8–16% in NT and 15–25% in CP and MP. From 1994 to 2000, concentrations of organic C and N decreased by 1% with hairy vetch and crimson clover, 2–6% with HN and FN, and 6–18% with the control. With rye, organic C and N increased by 3–4%. Soil organic C and N concentrations can be conserved and/or maintained by reducing their loss through mineralization and erosion, and by sequestering atmospheric CO_2 and N_2 in the soil using NT with cover crops and N fertilization. These changes in soil management improved soil quality and productivity. Non-legume (rye) was better than legumes (hairy vetch and crimson clover) and N fertilization in increasing concentrations of soil organic C and N.

Keywords: Management practices; Organic carbon; Organic nitrogen; Sandy loam; Southeast USA

1. Introduction

Concentrations of organic C and N are good indicators of soil quality and productivity due to their

* Corresponding author. Tel.: +1-478-825-6810; fax: +1-478-825-6376.
E-mail address: sainjuu@mail.fvsu.edu (U.M. Sainju).

0167-1987/02/$ – see front matter
PII: S0167-1987(01)00244-6

favorable effects on physical, chemical, and biological properties (Bauer and Black, 1994; Doran and Parkin, 1994). They play critical role in nutrient cycling, water retention, root growth (Sainju and Kalisz, 1990; Sainju and Good, 1993), plant productivity, and environmental quality. Their concentrations in the soil can be influenced by management practices, such as tillage, cover cropping, and N fertilization (Franzluebbers et al., 1995a,b; Kuo et al., 1997a,b; Salinas-Garcia et al., 1997).

While tillage enhances mineralization of soil organic C and N by incorporating crop residue, disrupting soil aggregates, and increasing aeration (Dalal and Mayer, 1986; Balesdent et al., 1990; Cambardella and Elliott, 1993), cover cropping can increase their concentrations by increasing residue addition to the soil (Hargrove, 1986; McVay et al., 1989; Kuo et al., 1997a,b). Practices that reduce residue incorporation and aggregate degradation, such as NT or minimum till, also may conserve and/or maintain concentrations of organic C and N (Doran, 1987; Havlin et al., 1990; Franzluebbers et al., 1995b). Similarly, N fertilization may increase concentrations of organic C and N due to increased plant biomass production (Blevins et al., 1983; Liang and Mackenzie, 1992; Gregorich et al., 1996; Omay et al., 1997).

Increased CO_2 and N_2O concentrations in the atmosphere that increase global warming are a major concern. One of the ways to help to reduce CO_2 and N_2O concentrations is to fix them in the plants and sequester in the soil. It has been known that agricultural soils can be used as sink to sequester atmospheric C and N (Lal and Kimble, 1997; Paustian et al., 1997). While non-legume cover crops and N fertilization can fix atmospheric C, and legume cover crops fix both C and N in the plants by increasing biomass production, NT or minimum till can reduce the rate of plant residue decomposition by placing the residues at the soil surface or by reducing their degree of incorporation into the soil (Doran, 1987; Havlin et al., 1990; Franzluebbers et al., 1995b). Little information is available about the effects of the combination of tillage, cover crops, and N fertilization on the concentrations of organic C and N in the soil and their impacts on the concentrations of the atmospheric C and N. Our objectives were to: (1) determine the amounts of C and N contributed by cover crops in the soil, (2) examine the long-term effects of tillage, cover crop, and N fertilization on soil organic C and N concentrations, (3) compare the effects of legume and non-legume cover crops and N fertilization rates on their concentrations, and (4) determine the best management that can conserve and/or maintain their concentrations.

2. Materials and methods

2.1. Field methods

2.1.1. Experiment 1

Experiment 1 was initiated in September 1994 at the Agricultural Research Station farm, Fort Valley State University, Fort Valley, GA. The soil was a Norfolk sandy loam (fine-loamy, siliceous, thermic, Typic Kandiudults) (FAO classification: Orthic Luvisols) with pH 6.5 and sand concentration of 650 g kg^{-1}, silt 250 g kg^{-1}, clay 100 g kg^{-1}, bulk density 1.39 Mg m^{-3}, and concentrations of 23.9 Mg organic C ha^{-1} and 1.95 Mg organic N ha^{-1} at the 0–20 cm depth. Cropping history for the last 10 years was double cropping of wheat (*Triticum* spp.) and soybean (*Glycine max* L. (Merr.)) for 2 years followed by alfalfa (*Medicago sativa* L.) for 8 years.

The treatments consisted of three levels of tillage (no-till, NT; chisel plowing, CP; and moldboard plowing, MP), two cover crop management systems (hairy vetch vs. no hairy vetch (winter weeds)), and three rates of N fertilization (0, 90 and 180 kg N ha^{-1}). The CP (or reduced tillage) consisted of harrowing to a depth of 10–15 cm, followed by chiseling to a depth of 20–25 cm and leveling with an S-tine harrow. Similarly, MP (or conventional tillage) consisted of harrowing, followed by MP to a depth of 20–25 cm and leveling. Nitrogen fertilizer was applied for tomato, not for cover crops. The 180 kg N ha^{-1} is the recommended rate of N fertilization for tomato in central Georgia (University of Georgia, 1995). Because of high concentration (50–70 kg ha^{-1}) of residual inorganic N in the soil, no N fertilizer was applied for silage corn. The treatments were arranged in a split-split plot design with tillage as the main plot, cover crop as the split plot, and N fertilization as the split-split plot treatment. Each treatment had three replications. The split-split plot size was $7.2 \times 7.2\,m^2$. The size of the guard rows was 0.9 m.

The CP and MP plots were tilled two times a year: in September or October for cover crop planting and in April of next year for tomato or silage corn planting. Plots were harrowed 2–3 times until plant residues were broken into small pieces and soil particles were loosened before plowing was done. The NT plots were left undisturbed except for drilling cover crop and silage corn seeds, transplanting tomato seedlings, and hand-weeding at the soil surface. Treatments were applied in the same plots from 1994 to 1999.

In September or October, 1994–1998, hairy vetch seed inoculated with *Rhizobium leguminosarum* (bv. viceae) was drilled at 28 kg ha^{-1}, with a row spacing of 15 cm. No fertilizer, herbicide, or insecticide was applied. In late March or early April of the following year, hairy vetch was harvested at flowering from 0.2 to 2 m^2 areas within the plot for yield and C and N concentration determinations before it was killed. In the no hairy vetch plot, weeds (dominated by henbit (*Lamium amplexicaule* L.) and cut-leaf evening primrose (*Oenolthea laciniate* L.)) were collected as above. After a subsample was collected, plant residue was returned to the same plot and uniformly spread. Plant samples were oven-dried at 60°C, weighed, and ground to pass through a 1 mm screen for C and N analysis. After sampling was done, cover crop and weeds were mowed with a rotary mower in all plots and killed either by spraying 3.36 kg a.i. ha^{-1} of glyphosate (*N*-(phosphonomethyl)glycine) in NT plots or incorporated into the soil by harrowing in CP and MP plots. Residues were allowed to decompose in the soil for 2 weeks before tomato seedlings were transplanted or corn seeds were drilled.

Tomato was grown from April to August, 1995–1997. At tomato transplanting in late April, P (from triple superphosphate [$Ca(H_2PO_4)_2$], 46% P) and K (from muriate of potash (KCl), 60% K) fertilizers were broadcast at 56 kg ha^{-1} each based on the soil test. At the same time, diazinon [diethyl-*O*-(2-isopropyl-6-methyl-4-pyrimidinyl)phosphorothioate] (3.35 kg a.i. ha^{-1}) was applied to control cutworms and 0.57 kg ha^{-1} of trifluralin [2,6-dinitro-*N*-dipropyl-4-(trifluoromethyl)benzeneamine] was applied to control weeds. Fertilizers, pesticide, and herbicide were incorporated into the soil by plowing in CP and MP plots and left at the soil surface in NT plots. The N fertilizer (nitrate of soda ($NaNO_3$), 16% N) was split into three rates and each was broadcast at 3-week intervals from the date of transplanting. Weeds in NT plots were controlled by hand-weeding with a spade at the soil surface every week throughout the growth. Five-week-old tomato (cv. Sunbeam) seedlings were hand-transplanted at a spacing of $0.9 \times 0.9\,m^2$ in eight-row plots. Starter solution containing 3 g l^{-1} (equivalent to 0.4 kg ha^{-1}) of N, P, and K was applied to each tomato plant after 1 week to encourage early establishment.

Silage corn was grown from April to August, 1998 and 1999. At corn planting in late April, P fertilizer at 67 kg ha^{-1} and K fertilizer at 84 kg ha^{-1} were broadcast. The sources of P and K fertilizers were similar as for tomato. Corn (cv. McNair 508) was drilled at 70,000 seeds ha^{-1} (0.9 m spacing). Within a day of planting, 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 to control post-emergence of weeds. Irrigation was applied immediately after fertilization and as needed to prevent water stress, both for tomato and corn.

In July and August, 1995–1997, tomato fruits were harvested every 3–4 days as the color turned from green to pink. Fruits were picked from five plants (4.05 m^2 area) in the middle rows and total yield per plot was determined. Similarly, in August, 1998 and 1999, silage corn was harvested from two middle rows (12.6 m^2 area) for biomass yield. After tomato and corn were harvested, leftover plant residues was removed from the plot. Thereafter, in August or September, 1994–1999, soil samples were taken from 0 to 20 cm depth from five places in the middle rows with a push tube (5 cm diameter). After visible plant residues were separated, soil samples were composited, air-dried, and crushed to pass a 2 mm sieve.

2.1.2. Experiment 2

Experiment 2 was started in September 1994 in Fort Valley, GA, on a Greenville fine sandy loam (fine-loamy, kaolinitic, thermic, Rhodic Kandiudults) (FAO classification: Chromic Luvisols). The soil had 650 g of sand, 200 g silt, and 150 g clay kg^{-1} soil, pH 6.0, bulk density 1.49 Mg m^{-3}, and concentrations of 18.1 Mg organic C ha^{-1} and 1.39 Mg organic N ha^{-1} at the 0–20 cm depth. Cropping history for the past 5 years was corn and fallow in alternate years.

The experiment consisted of six main treatments (rye, hairy vetch, crimson clover, control, HN, and FN) in a randomized complete block design with four replications. The control contained neither cover crop nor N fertilization. The HN was the half rate (90 kg N ha^{-1} for tomato or 80 kg N ha^{-1} for eggplant) and FN was the full rate (180 kg N ha^{-1} for tomato or 160 kg N ha^{-1} for eggplant) of N fertilization. Because the objective was to compare the effects of cover crops and N fertilization rates, N fertilization was not used as split-plot treatment, as was done in Experiment 1. As for tomato, the recommended rate of N fertilization for eggplant in central Georgia is 160 kg N ha^{-1}. The plot size was 4.5 m × 7.2 m. The size of guard rows was 0.9 m. Treatments were applied in the same plots from 1994 to 2000 except in 1998 when plots were left fallow.

As in Experiment 1, plots were tilled two times a year: in September or October for cover crop planting and in April of next year for tomato or eggplant transplanting. The tillage operation consisted of harrowing (12–15 cm depth), followed by leveling (10–15 cm depth). The harrowing operation consisted of disking to break the soil clods into smaller pieces and to incorporate plant residue into the soil. The leveling consisted of smoothening the soil surface with an S-tine harrow after disking was done. Plots were harrowed 2–3 times until plant residues were broken into smaller pieces and soil loosened before leveling and planting were done. Following tillage, hairy vetch seed was drilled at 28 kg ha^{-1}, crimson clover at 25 kg ha^{-1}, and rye at 80 kg ha^{-1} at a 15 cm spacing between the rows in September or October, 1994–1999. Hairy vetch seed was inoculated with *R. leguminosarum* (bv. viceae) and crimson clover seed was inoculated with *R. trifolii* before drilling. No N, P, and K fertilizers, herbicide, or pesticide were applied to the cover crops.

In late March or early April of the following year, cover crops were harvested at flowering from 0.2 to 2 m^2 areas within each plot for biomass yield and C and N concentrations determination. In the control and N fertilization plots, weeds dominated by henbit (*L. amplexicaule* L.) and cut-leaf evening primrose (*Oenothera laciniata* L.) were collected as above. After subsample had been collected, plant residue was uniformly spread to the same place where it had been collected from. Plants samples were oven-dried at 60°C, weighed, and ground to pass a 1 mm sieve for C and N analysis. After sampling had been done, cover crops and weeds were mowed with a tractor-drawn rotary mower and residues were incorporated into the soil by disking 2–3 times. Residues were allowed to decompose in the soil for 2 weeks before tomatoes and eggplants were transplanted.

Tomato was grown from April to August, 1995–1999 and eggplant in 2000. At tomato and eggplant transplanting in late April, P fertilizer was broadcast at 56 kg ha^{-1} for tomato and 50 kg ha^{-1} for eggplant and K fertilizer was broadcast at 56 kg ha^{-1} for tomato and 60 kg ha^{-1} for eggplant based on the soil test. As in Experiment 1, N fertilizer was applied at 3-week intervals and pesticide and herbicide were applied at transplanting (fertilizer source, herbicide, and pesticide were similar as for tomato in Experiment 1). In late April, 4-week-old marketable tomato (cv. Mountain Pride) or eggplant (cv. Migelle) seedlings were hand-transplanted at a spacing of 0.9 × 0.9 m^2 in five-row plots. Starter solution containing 3 g N, P, and K per liter (or 0.4 kg ha^{-1}) was applied to tomato or eggplant after 1 week to improve early establishment. Plots were irrigated immediately after fertilization and as needed to prevent water stress.

In July and August, tomato and eggplants were harvested every 3–4 days from five plants (0.9 m × 4.5 m) in the middle rows and marketable fruit yield was determined. Following removal of leftover biomass, in August, soil samples were collected from five places in the middle rows at 0–20 cm depth with a push tube (5 cm diameter), composited, air-dried, ground, and passed to a 2 mm sieve.

2.2. Laboratory analysis

Nitrogen (g kg^{-1} plant) in the cover crop sample was determined by the H_2SO_4–H_2O_2 method as described by Kuo et al. (1997b). Carbon (g kg^{-1}) in the cover crop sample was determined by the Walkley–Black method (Nelson and Sommers, 1996), assuming all plant C was oxidized during digestion. Cover crop C or N concentration (kg ha^{-1}) was determined by multiplying biomass yield by C or N (g kg^{-1}). The C:N ratio in the cover crop sample was determined by dividing C concentration by N concentration. Concentrations of C and N in cover crops in 1995 in Experiment 1 and in 1995 and 1998 in Experiment 2 were not determined.

Soil organic C (g kg^{-1} soil) was determined by the Walkley–Black method. Total N (g kg^{-1}) was determined by the Kjeldahl method (Bremner, 1996). The NH_4^+ and NO_3^- (mg kg^{-1}) were determined by steam distillation (Mulvaney, 1996) after extraction with 2 M KCl. Organic N was determined as the difference between total N and NH_4^+ and NO_3^-. Soil organic C or N concentration (Mg ha^{-1}) at 0–20 cm depth was calculated by multiplying organic C or N (g kg^{-1}) by bulk density and depth. Because bulk density was not significantly affected by treatments and interactions at the beginning and end of the experiment, the average value was used to calculate organic C or N concentration for a treatment.

2.3. Data analysis

Data were analyzed using the GLM procedure of SAS after testing for homogeneity of variance (SAS, 1987). Year was considered as the split-plot treatment for analysis. Means were separated by the least significant difference (LSD) test when treatments and interactions were significant. Statistical significance was evaluated at $P < 0.05$.

3. Results

3.1. Climate

Average monthly temperature from 1996 to 2000 when crops were grown were similar to the 41 years average (Fig. 1A). Total monthly and yearly rainfall, however, varied from year to year and the 41 years average (Fig. 1B).

3.2. Cover crop carbon and nitrogen concentrations

Tillage, N fertilization to tomato, and their interactions were not significant for cover crop C and N concentrations in Experiment 1. Hairy vetch had two to eightfold greater C and N concentrations than winter weeds in the no hairy vetch plot (Table 1). The C:N ratio was lower in hairy vetch than in winter weeds. Carbon concentration varied from 656 kg ha^{-1} in winter weeds in 1996 to 2 952 kg ha^{-1} in hairy vetch in 1999 and N concentration varied from 27 kg ha^{-1} in winter weeds in 1997 to 242 kg ha^{-1} in hairy vetch in 1998.

In Experiment 2, C and N concentrations were greater in rye, hairy vetch, and crimson clover than in winter weeds in the control and N fertilization treatments, except for N concentration in rye in 1996 (Table 2). Rye had greater C concentration than hairy

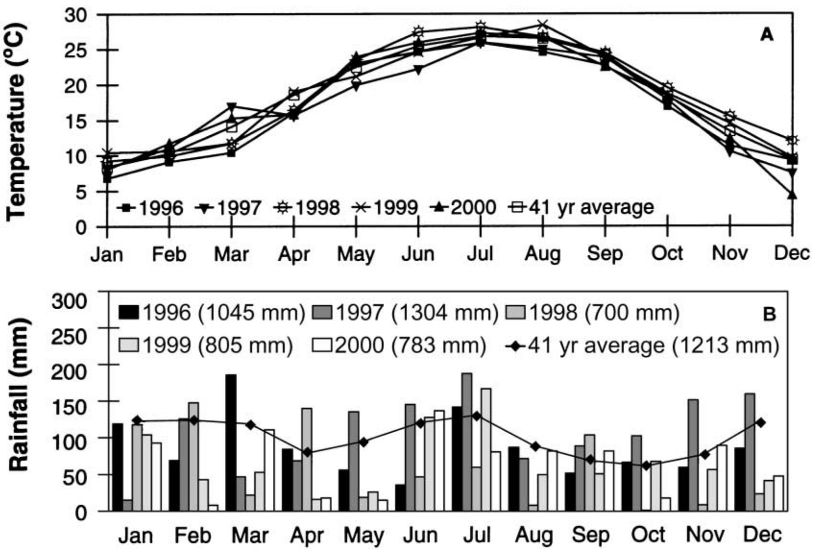

Fig. 1. Average monthly temperature (A) and total monthly rainfall (B) from 1996 to 2000 near the experimental site in Fort Valley, GA. The values in parenthesis represent total rainfall from January to December in the year.

Table 1
Carbon and N concentrations in cover crop and winter weeds from 1996 to 1999 in Experiment 1[a]

Cover crop	1996	1997	1998	1999
C concentration (kg ha^{-1})				
Hairy vetch	2390 a	1802 a	2668 a	2952 a
No hairy vetch[b]	656 b	817 b	772 b	732 b
N concentration (kg ha^{-1})				
Hairy vetch	205 a	77 a	242 a	196 a
No hairy vetch	37 b	27 b	30 b	40 b
C:N ratio				
Hairy vetch	11.7 b	23.6 b	11.1 b	15.0 b
No hairy vetch	18.0 a	32.3 a	28.3 a	19.9 a

[a] Within a column and a set, numbers followed by different letters are significantly different ($P < 0.05$, LSD test).
[b] Contains winter weeds dominated by henbit (*L. amplexicaule* L.) and cut-leaf evening primrose (*O. laciniata* L.).

Table 2
Carbon and N concentrations in cover crops and winter weeds from 1996, 1997, 1999 and 2000 in Experiment 2[a]

Treatment	1996	1997	1999	2000
C concentration (kg ha^{-1})				
Rye	2888 a	3020 a	3704 a	3000 a
Hairy vetch	2313 a	1911 b	704 c	1723 bc
Crimson clover	2863 a	2663 a	1231 b	2285 ab
Control[b]	836 b	595 c	305 c	835 c
HN[c]	750 b	655 c	299 c	1340 c
FN[d]	850 b	685 c	324 c	944 c
N concentration (kg ha^{-1})				
Rye	77 b	137 b	78 a	86 b
Hairy vetch	167 a	207 a	73 a	173 a
Crimson clover	147 a	299 a	87 a	166 a
Control	45 b	49 c	18 b	39 c
HN	43 b	52 c	23 b	56 bc
FN	48 b	54 c	25 b	50 c
C:N ratio				
Rye	38.3 a	25.3 a	49.2 a	35.2 a
Hairy vetch	13.8 b	9.2 b	9.8 b	9.8 d
Crimson clover	19.6 b	12.3 b	14.3 b	13.8 d
Control	18.8 b	12.3 b	17.9 b	23.1 b
HN	17.4 b	12.6 b	12.6 b	24.4 b
FN	17.7 b	12.7 b	14.1 b	19.4 c

[a] Within a column and a set, numbers followed by different letters are significantly different ($P < 0.05$, LSD test).
[b] Contains winter weeds dominated by henbit (*L. amplexicaule* L.) and cut-leaf evening primrose (*O. laciniata* L.).
[c] Half N rate for tomato (90 kg N ha^{-1}) or eggplant (80 kg N ha^{-1}).
[d] Full N rate for tomato (180 kg N ha^{-1}) or eggplant (160 kg N ha^{-1}).

Table 3
Effects of tillage, cover crop, and N fertilization on fresh-market tomato and silage corn (dry matter weight) yield in Experiment 1[a]

Treatment	Tomato (Mg ha^{-1})		Silage corn (Mg ha^{-1})	
	1996	1997	1998	1999
Tillage[b]				
NT	35.0 b	32.1 a	14.5 a	20.3 a
CP	66.4 a	33.5 a	14.6 a	21.5 a
MP	62.9 a	30.5 a	15.7 a	21.1 a
Cover crop				
Hairy vetch	56.7 a	34.0 a	14.8 a	24.6 a
No hairy vetch	53.9 a	33.4 a	15.0 a	17.3 b
N fertilization (kg N ha^{-1})				
0	49.5 b	26.6 b	15.5 a	21.6 a
90	58.1 a	36.0 a	14.9 a	21.1 a
180	56.6 a	33.6 a	14.4 a	20.2 a

[a] Within a column and a set, numbers followed by different letters are significantly different ($P < 0.05$, LSD test).
[b] Tillage are NT, no-till; CP, chisel plowing; and MP, moldboard plowing.

vetch in 1997, 1999 and 2000 and than crimson clover in 1999. In contrast, hairy vetch and crimson clover had greater N concentration than rye in 1996, 1997 and 2000. Carbon and N concentrations in winter weeds in the control and N fertilization treatments were similar. Carbon concentration ranged from 299 kg ha^{-1} in winter weeds in 1999 to 3704 kg ha^{-1} in rye in 1999. Nitrogen concentration ranged from 23 kg ha^{-1}

Table 4
Effects of cover crops and N fertilization on fresh-market tomato and eggplant yield in Experiment 2[a]

Treatment	Tomato (Mg ha^{-1})			Eggplant (Mg ha^{-1}), 2000
	1996	1997	1999	
Rye	19.0 b	13.6 c	37.0 c	21.0 c
Hairy vetch	40.2 a	31.5 a	75.2 a	52.1 a
Crimson clover	40.9 a	30.0 a	65.4 ab	45.5 a
Control[b]	20.0 b	17.3 bc	56.1 b	23.7 c
HN[c]	39.1 a	27.9 ab	66.2 ab	44.3 ab
FN[d]	43.1 a	27.0 ab	67.4 ab	37.1 b

[a] Within a column, numbers followed by different letters are significantly different ($P < 0.05$, LSD test).
[b] Control contains no cover crop or N fertilization.
[c] Half N rate for tomato (90 kg N ha^{-1}) or eggplant (80 kg N ha^{-1}).
[d] Full N rate for tomato (180 kg N ha^{-1}) or eggplant (160 kg N ha^{-1}).

in winter weeds in 1999 to 299 kg ha^{-1} in crimson clover in 1997. The C:N ratio was greater in rye than in hairy vetch, crimson clover, and winter weeds.

3.3. Summer crop yields

Tillage, cover crop, and N fertilization were significant but their interactions were not significant for tomato and silage corn yields in Experiment 1. Tomato yield was lower in NT than in CP and MP in 1996 but yields were not influenced by tillage in 1997, 1998 and 1999 (Table 3). Corn yield was greater with than without hairy vetch in 1999 but yields were not influenced by cover crop in 1996–1998. Tomato yield was greater with 90 and 180 than with 0 kg N ha^{-1} in 1996 and 1997. In 1998 and 1999, N fertilizer was not applied to corn. As a result, residual soil N did not influence corn yield.

Table 5
Effects of tillage, cover crop, and N fertilization on concentration of soil organic C at 0–20 cm depth from 1994 to 1999 in Experiment 1

Tillage[a]	Cover crop[b]	N fertilization (kg N ha^{-1})	Organic C concentration (Mg ha^{-1})								
			1994	1995	1996	1997	1998	1999	LSD[c]	Mean	Mean[d]
NT	HV	0	23.9	24.2	28.4	24.5	23.9	24.4	3.6	24.9	23.5
		90	23.9	21.3	26.9	23.9	23.9	24.3	2.8	24.0	23.2
		180	23.9	21.3	24.8	22.9	23.6	24.2	3.3	23.5	23.5
	NHV	0	23.9	20.5	26.0	21.8	21.4	19.9	3.4	22.2	–
		90	23.9	21.6	24.5	22.8	21.2	19.8	3.2	22.3	–
		180	23.9	22.5	28.8	24.9	21.0	19.8	3.8	23.5	–
CP	HV	0	23.9	21.3	23.3	23.1	20.7	20.1	3.6	22.1	22.1
		90	23.9	22.1	20.1	23.7	20.7	20.3	3.2	21.8	21.7
		180	23.9	24.7	27.1	26.0	20.7	19.9	2.5	23.7	23.6
	NHV	0	23.9	23.2	22.7	21.4	21.6	20.1	3.6	22.2	–
		90	23.9	21.5	20.2	22.0	22.6	20.0	3.7	21.7	–
		180	23.9	24.7	23.2	24.8	23.7	20.3	4.0	23.4	–
MP	HV	0	23.9	19.4	23.2	19.4	21.9	20.8	3.0	21.4	21.1
		90	23.9	18.0	17.9	18.2	22.1	21.0	3.6	20.2	20.0
		180	23.9	19.0	21.3	20.4	22.1	20.0	1.8	21.1	20.5
	NHV	0	23.9	20.4	21.1	19.5	20.1	20.1	2.2	20.8	–
		90	23.9	17.0	19.7	18.1	20.1	20.3	1.7	19.9	–
		180	23.9	18.2	18.0	19.1	20.1	20.3	4.1	19.9	–
LSD			–	3.1	5.3	5.5	2.9	2.8	–	1.5	1.0
Mean			23.9	21.2	23.2	22.0	21.8	20.9	1.3	–	–
Mean across cover crop and N fertilization[e]											
NT			23.9 a	21.9 a	26.6 a	23.5 a	22.5 a	22.1 a	1.4	23.4 a	–
CP			23.9 a	22.9 a	22.8 ab	23.5 a	21.7 a	20.1 b	1.7	22.5 ab	–
MP			23.9 a	18.6 b	20.2 b	19.1 b	21.1 a	20.4 b	1.0	20.6 b	–
Mean across tillage and cover crop[e]											
0 kg N ha^{-1}			23.9 a	21.5 a	24.1 a	21.6 a	21.6 a	20.9 a	1.5	22.3 a	–
90 kg N ha^{-1}			23.9 a	20.2 b	21.5 b	21.4 a	21.8 a	21.0 a	1.3	21.6 b	–
180 kg N ha^{-1}			23.9 a	21.7 a	23.9 a	23.0 a	21.9 a	20.8 a	1.7	22.5 a	–

[a] Tillage are NT, no-till; CP, chisel plowing; and MP, moldboard plowing.
[b] Cover crops are HV, hairy vetch; and NHV, no hairy vetch (winter weeds).
[c] LSD between treatments within a row or column ($P = 0.05$).
[d] Mean across year and cover crop.
[e] Within a column and a set, numbers followed by different letters are significantly different ($P < 0.05$, LSD test).

In Experiment 2, tomato and eggplant yields were greater with hairy vetch and crimson clover than with rye or the control in 1996, 1997 and 2000 (Table 4). Yields with hairy vetch and crimson clover were similar to those with HN and FN in 1996, 1997 and 1999. Yields with rye and the control were similar and both were lower than those with HN and FN in 1996, 1997 and 2000.

3.4. Soil organic carbon concentration

Statistical analysis indicated that treatments and their interactions were significant for soil organic C in Experiments 1 and 2. In Experiment 1, NT with hairy vetch and without N fertilization maintained a greater concentration of organic C than MP with or without hairy vetch and N fertilization from 1995 to 1999 (Table 5). Mean organic C across years was greater in NT with hairy vetch and with or without N fertilization, in NT without hairy vetch and with 180 kg N ha^{-1}, and in CP with or without hairy vetch and with 180 kg N ha^{-1} than in MP with or without hairy vetch and N fertilization. Averaged across cover crops and years, organic C was greater in NT with or without N fertilization and in CP with 180 kg N ha^{-1} than in MP with or without N fertilization. Averaged across cover crops and N fertilization, organic C was greater in NT and CP than in MP in 1995 and 1997,

Table 6
Effects of cover crops and N fertilization on concentrations of soil organic C and N at 0–20 cm depth from 1994 to 2000 in Experiment 2

Treatment	1994	1995	1996	1997	1998	1999	2000	LSD[a]	Mean
Organic C (Mg ha^{-1})									
Rye	18.1	18.9	18.3	18.5	18.3	18.5	18.7	1.3	18.4
Hairy vetch	18.1	18.7	18.2	17.6	17.3	17.7	18.0	1.3	17.9
Crimson clover	18.1	17.8	18.1	17.0	17.7	17.7	17.9	1.4	17.8
Control[b]	18.1	17.8	16.6	16.3	16.1	15.6	14.9	1.5	16.5
HN[c]	18.1	18.0	17.4	17.2	17.4	17.5	17.1	0.8	17.5
FN[d]	18.1	17.9	17.2	17.2	17.4	17.4	17.1	0.7	17.5
LSD	–	1.1	1.3	2.0	1.4	2.1	2.2	–	0.3
Mean	18.1	18.2	17.6	17.3	17.4	17.4	17.3	0.7	–
Organic N (Mg ha^{-1})									
Rye	1.39	1.43	1.45	1.43	1.44	1.45	1.45	0.14	1.43
Hairy vetch	1.39	1.41	1.46	1.38	1.38	1.41	1.41	0.13	1.40
Crimson clover	1.39	1.36	1.33	1.36	1.36	1.44	1.42	0.10	1.38
Control	1.39	1.31	1.29	1.28	1.28	1.32	1.31	0.12	1.31
HN	1.39	1.31	1.32	1.34	1.31	1.33	1.33	0.11	1.33
FN	1.39	1.32	1.32	1.35	1.34	1.39	1.40	0.10	1.36
LSD	–	0.12	0.12	0.12	0.13	0.13	0.12	–	0.05
Mean	1.39	1.36	1.36	1.36	1.35	1.39	1.39	0.04	–
C:N ratio									
Rye	13.1	13.2	12.6	12.9	12.7	13.1	12.9	1.3	12.9
Hairy vetch	13.1	13.4	12.5	12.7	12.6	12.6	12.8	1.0	12.8
Crimson clover	13.1	13.1	13.6	12.5	13.0	12.3	12.6	1.0	12.9
Control	13.1	13.5	12.9	12.7	12.5	11.8	11.4	1.1	12.6
HN	13.1	13.7	13.2	12.9	13.2	13.1	12.9	1.2	13.2
FN	13.1	13.6	13.0	12.7	13.0	12.5	12.2	1.0	12.8
LSD	–	1.0	1.1	0.9	0.8	1.3	1.2	–	0.6
Mean	13.1	13.4	13.0	12.7	12.8	12.6	12.6	0.8	–

[a] LSD between treatments within a row or a column ($P = 0.05$).
[b] Control contains no cover crop or N fertilization.
[c] Half N rate for tomato (90 kg N ha^{-1}) or eggplant (80 kg N ha^{-1}).
[d] Full N rate for tomato (180 kg N ha^{-1}) or eggplant (160 kg N ha^{-1}).

greater in NT than in MP in 1996, and greater in NT than in CP and MP in 1999. Averaged across tillage and cover crops, organic C was greater with 0 and 180 than with 90 kg N ha^{-1} in 1995 and 1996.

Averaged across cover crops, N fertilization, and years, organic C was 14% greater in NT than in MP (Table 5). Averaged across tillage, N fertilization, and years, organic C was 3% greater with than without hairy vetch. Averaged across tillage, cover crops, and years, organic C was 4% greater with 180 and 0 than with 90 kg N ha^{-1}. From 1994 to 1999, organic C decreased by 8% in NT, 16% in CP, 15% in MP, 13% with 0 and 180 kg N ha^{-1}, and 12% with 90 kg N ha^{-1}.

In Experiment 2, rye maintained a greater concentration of organic C than did the control from 1995 to 2000 (Table 6). Concentration of organic C was also greater with hairy vetch and crimson clover than with the control in 1996, 1999 and 2000, and greater with

Table 7
Effects of tillage, cover crop, and N fertilization on concentration of soil organic N at 0–20 cm depth from 1994 to 1999 in Experiment 1

Tillage[a]	Cover crop[b]	N fertilization (kg N ha^{-1})	Organic N concentration (Mg ha^{-1})								
			1994	1995	1996	1997	1998	1999	LSD[c]	Mean	Mean[d]
NT	HV	0	1.95	2.08	2.51	2.38	1.65	1.72	0.59	2.05	1.95
		90	1.95	1.82	2.47	2.02	1.74	1.74	0.42	1.95	1.90
		180	1.95	1.72	2.02	2.33	1.77	1.76	0.61	1.92	1.95
	NHV	0	1.95	1.93	2.29	1.70	1.60	1.60	0.57	1.84	–
		90	1.95	1.80	2.33	1.94	1.57	1.48	0.45	1.84	–
		180	1.95	2.05	2.54	2.15	1.62	1.56	0.49	1.98	–
CP	HV	0	1.95	1.69	1.88	1.99	1.50	1.51	0.37	1.76	1.76
		90	1.95	1.88	1.71	2.03	1.52	1.53	0.33	1.77	1.79
		180	1.95	1.80	2.25	2.25	1.51	1.55	0.21	1.89	1.89
	NHV	0	1.95	1.63	2.06	1.78	1.71	1.43	0.47	1.76	–
		90	1.95	2.03	2.04	1.78	1.69	1.41	0.36	1.82	–
		180	1.95	2.04	2.18	2.08	1.73	1.45	0.55	1.90	–
MP	HV	0	1.95	1.45	2.01	1.52	1.60	1.41	0.19	1.66	1.71
		90	1.95	1.38	1.58	1.49	1.64	1.43	0.21	1.58	1.58
		180	1.95	1.53	1.82	1.71	1.62	1.39	0.23	1.67	1.66
	NHV	0	1.95	1.99	1.98	1.44	1.62	1.55	0.53	1.76	–
		90	1.95	1.31	1.68	1.40	1.63	1.51	0.20	1.58	–
		180	1.95	1.82	1.79	1.69	1.64	1.53	0.42	1.65	–
LSD			–	0.43	0.59	0.62	0.16	0.22	–	0.16	0.11
Mean			1.95	1.75	2.06	1.87	1.63	1.53	0.19	–	–
Mean across cover crop and N fertilization[e]											
NT			1.95 a	1.90 a	2.36 a	2.09 a	1.66 a	1.64 a	0.20	1.93 a	–
CP			1.95 a	1.85 a	2.02 ab	1.98 ab	1.61 a	1.48 b	0.15	1.81 a	–
MP			1.95 a	1.50 b	1.81 b	1.54 b	1.63 a	1.47 b	0.12	1.65 b	–
Mean across tillage and cover crop[e]											
0 kg N ha^{-1}			1.95 a	1.80 a	2.12 a	1.80 b	1.62 a	1.54 a	0.17	1.80 ab	–
90 kg N ha^{-1}			1.95 a	1.70 a	1.97 a	1.78 b	1.63 a	1.52 a	0.13	1.76 b	–
180 kg N ha^{-1}			1.95 a	1.74 a	2.10 a	2.04 a	1.65 a	1.54 a	0.17	1.84 a	–

[a] Tillage are NT, no-till; CP, chisel plowing; and MP, moldboard plowing.
[b] Cover crops are HV, hairy vetch; and NHV, no hairy vetch (winter weeds).
[c] LSD between treatments within a row or column ($P = 0.05$).
[d] Mean across year and cover crop.
[e] Within a column and a set, numbers followed by different letters are significantly different ($P < 0.05$, LSD test).

HN and FN than with the control in 2000. Mean organic C across years was 12% greater with rye, 8% greater with hairy vetch and crimson clover, and 6% greater with HN and FN than with the control. From 1994 to 2000, organic C was increased by 3% with rye, but decreased by 1% with hairy vetch and crimson clover, 6% with HN and FN, and 18% with the control.

3.5. Soil organic nitrogen concentration

As with organic C, treatments and their interactions were significant for soil organic N in Experiments 1 and 2. In Experiment 1, with hairy vetch, organic N concentration was greater in NT without N fertilization than in MP with or without N fertilization in 1995, 1997 and 1999 (Table 7). With or without N fertilization, mean organic N across years was greater in NT with hairy vetch than in MP with or without hairy vetch. Mean organic N across cover crops and years was greater in NT with or without N fertilization or in CP with 180 kg N ha^{-1} than in CP with 0 kg N ha^{-1} or in MP with or without N fertilization. Averaged across cover crops and N fertilization, organic N was greater in NT and CP than in MP in 1995, greater in NT than in MP in 1996 and 1997, and greater in NT than in CP and MP in 1999. Averaged across tillage and cover crops, organic N was greater with 180 than with 0 and 90 kg N ha^{-1} in 1997.

Averaged across cover crops, N fertilization, and years, organic N was 17% greater in NT and 10% greater in CP than in MP (Table 7). Averaged across tillage, cover crops, and years, organic N was 5% greater with 180 kg N ha^{-1} than with 90 kg N ha^{-1}. From 1994 to 1999, organic N decreased by 16% in NT, 24% in CP, 25% in MP, 21% with 0 and 180 kg N ha^{-1}, and 22% with 90 kg N ha^{-1}.

In Experiment 2, as with organic C, rye maintained a greater concentration of organic N than did the control from 1995 to 2000 (Table 6). Organic N was also greater with hairy vetch than with the control in 1996. Mean organic N across years was 9% greater with rye, 7% greater with hairy vetch, 5% greater with crimson clover, and 4% greater with FN than with the control. From 1994 to 2000, organic N increased by 4% with rye, 2% with crimson clover, and 1% with hairy vetch and FN, but decreased by 4% with HN and 6% with the control.

Table 8
Effect of cover crop on soil C:N ratio (mean across tillage and N fertilization) at 0–20 cm depth from 1994 to 1999 in Experiment 1[a]

Cover crop[b]	1994	1995	1996	1997	1998	1999	LSD[c]	Mean
HV	12.3 a	12.6 a	11.7 a	12.4 a	13.7 a	14.0 a	0.5	12.6 a
NHV	12.3 a	12.1 a	11.0 b	11.6 b	12.9 b	13.4 a	0.8	12.4 a
Mean	12.3	12.4	11.4	12.0	13.3	13.7	0.3	–

[a] Within a column, numbers followed by different letters are significantly different ($P < 0.05$, LSD test).
[b] Cover crops are HV, hairy vetch; and NHV, no hairy vetch (winter weeds).
[c] LSD between treatments within a row ($P = 0.05$).

3.6. Soil C:N ratio

Year and year × cover crop were significant for soil C:N ratio in Experiment 1 and year, treatment, year × treatment were significant in Experiment 2. The C:N ratio was greater with than without hairy vetch in 1996–1998 (Table 8). Mean ratio across years was not different between cover crops. In Experiment 2, the ratio was greater with crimson clover than with hairy vetch in 1996, greater with rye and HN than with the control in 1999, and greater with rye, hairy vetch, and crimson clover, and HN than with the control in 2000 (Table 6). Mean ratio across years was greater with HN than with the control.

4. Discussion

4.1. Cover crop carbon and nitrogen concentrations

Hairy vetch and crimson clover, being legumes, fix N from the atmosphere. Because of higher biomass yield and N, C and N concentrations were greater in legumes than in weeds in the control, HN, and FN treatments (Tables 1 and 2). As a result, legumes had lower C:N ratios. Rye had greater C concentration than did hairy vetch, crimson clover, and weeds because of greater biomass yield and C but lower N concentration than hairy vetch and crimson clover because of lower N. As a result, rye had greater C:N ratio. While N concentration in hairy vetch and crimson clover may have resulted from N fixation from the atmosphere and taken up from the soil, N concentration in rye and winter weeds may have resulted from N taken up from the soil.

4.2. Soil organic carbon and nitrogen concentrations

The greater soil organic C and N concentrations in NT than in CP or MP (Tables 5 and 7) may have resulted from the placement of plant residue at the soil surface, thereby reducing residue contact with soil microorganisms for decomposition (Havlin et al., 1990; Franzluebbers et al., 1995a; Salinas-Garcia et al., 1997). In contrast, incorporation of the residue to a greater depth in CP and MP may have resulted in its rapid decomposition in the soil, thereby resulting in lower organic C and N concentrations (Blevins et al., 1983; Doran, 1987). We believe that the larger difference in organic C and N concentrations between NT and MP in this experiment was probably a result of twice a year cultivation in MP plots for cover crop and summer crop planting, as opposed to once a year cultivation performed in other studies (Havlin et al., 1990; Franzluebbers et al., 1995a; Salinas-Garcia et al., 1997). Organic C and N concentrations decrease with increasing intensity and frequency of tillage (Franzluebbers et al., 1999).

Increased organic C and N concentrations with than without cover crops (Tables 5–7) can be attributed to increased C and N inputs from cover crops than from winter weeds (Tables 1 and 2). Increased organic C and N concentrations with rye, hairy vetch, and crimson clover have been observed by several researchers (Hargrove, 1986; Kuo et al., 1997a,b). The greater concentrations of organic C and N with rye than with hairy vetch or crimson clover may have resulted from its greater biomass yield, C concentration, and C:N ratio (Table 2), thereby slowing the rate of decomposition of rye in the soil. Increased organic C and N concentration with increasing rate of N fertilization may have resulted from increased biomass yield of summer crops (Tables 3 and 4) (Franzluebbers et al., 1995a; Omay et al., 1997; Salinas-Garcia et al., 1997).

The lower decline of concentrations of organic C and N in NT than in CP and MP from 1994 to 1999 suggests that NT can better conserve and/or maintain their concentrations in the soil, probably by reducing their loss through mineralization and erosion. Similarly, the increased concentrations with rye or the decreased decline with hairy vetch, crimson clover, HN, and FN compared with the control from 1994 to 2000 suggests that cover crops and N fertilization can better conserve and/or maintain organic C and N concentrations, probably by adding increased amount of plant residues to the soil. Non-legumes, such as rye, however, were more effective in maintaining organic C and N concentrations in the soil than legumes, such as hairy vetch and crimson clover, and N fertilization. Greater decline of organic C and N concentrations with the treatments in Experiment 1 than in Experiment 2 may have resulted from difference in soil texture, because soil in Experiment 2 had 5% more clay than in Experiment 1 (Sections 2.1.1 and 2.1.2). Increased clay concentration probably reduces the rate of mineralization of organic C and N.

The increased organic C and N concentrations in NT with hairy vetch compared with MP with or without vetch and N fertilization (Tables 5 and 7) or with cover crops and N fertilization compared with the control (Table 6) suggests that NT with cover crop and N fertilization can be successfully used to conserve and/or maintain organic C and N concentrations, particularly in the southeast USA where organic matter concentration is lower than in the northerly areas. Summer crop yields, however, were lower with rye than with hairy vetch, crimson clover, and N fertilization (Table 4), but were not affected by tillage practices, except in 1996 (Table 3). Summer crop yields were similar with legumes, HN, and FN. Therefore, best management would be to use NT with a mixture of legume and non-legume cover crops and N fertilization for conserving and/or maintaining soil organic C and N concentrations and for sustaining summer crop yields. Increased concentrations of organic C and N increase sequestration of atmospheric CO_2 and N_2 in the soil, thereby helping to mitigate their deleterious effects (Lal and Kimble, 1997; Paustian et al., 1997).

The significant year × cover crop interaction on soil C:N ratio suggests that variation in the amount of C and N contributed by cover crops and their rate of decomposition from year to year can alter C:N ratio of the soil. Non-significant ratio between cover crops, averaged over tillage, N fertilization, and years in Experiment 1 (Table 8) or between treatments averaged over years (except HN) in Experiment 2 (Table 6) suggests that organic C and N stabilize together in the soil (McGill and Cole, 1981), so that change in organic C is closely associated with change in organic N, regardless of tillage or cropping systems (Campbell and Souster, 1982; Uhlen, 1991; Paustian et al., 1992).

5. Conclusions

Carbon and N concentrations in cover crops varied from year to year and were greater in cover crops than in winter weeds in the N fertilization treatment to summer crops and the control without a cover crop or N fertilization. With or without N fertilization, soil organic C and N concentrations were greater in NT with hairy vetch than in MP with or without hairy vetch. Similarly, organic C and N concentrations were greater with rye, hairy vetch, crimson clover, and FN than with the control, with rye maintaining a greater concentration from 1995 to 2000. Mean soil C:N ratio between cover crops was relatively constant. Except in 1996, summer crop yields were similar between tillage treatments but were greater with hairy vetch and crimson clover than with rye or the control. The NT with hairy vetch cover crop can conserve and/or maintain organic C and N concentrations in the soil, thereby improving soil quality and productivity compared with MP with or without hairy vetch and N fertilization. Because of mixed results of legume and non-legume cover crops on soil C and N and summer crop yields, a mixture of legume and non-legume cover crops can sustain both summer crop yield and soil quality and productivity. Increasing organic C and N concentrations in the soil will help to reduce the deleterious effects of atmospheric C and N. The results can be applied to areas with soils and climate that support cover crop growth in the winter and have low soil organic matter concentration.

References

Balesdent, J.A., Mariotti, A., Boisgontier, D., 1990. Effects of tillage on soil organic carbon mineralization estimated from ^{13}C abundance in maize fields. J. Soil Sci. 41, 584–596.

Bauer, A., Black, A.L., 1994. Quantification of the effect of soil organic matter content on soil productivity. Soil Sci. Soc. Am. J. 58, 185–193.

Blevins, R.L., Thomas, G.W., Smith, M.S., Frye, W.W., Cornelius, P.L., 1983. Changes in soil properties after 10 years of continuous non-tilled and conventionally tilled corn. Soil Till. Res. 3, 135–136.

Bremner, J.M., 1996. Nitrogen-total. In: Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnson, C.T., Sumner, M.E. (Eds.), Methods of Soil Analysis. Part 3. Chemical Methods. SSSA Book Series, Vol. 5. Soil Science Society of America, Madison, WI, pp. 1085–1121.

Cambardella, C.A., Elliott, E.T., 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Sci. Soc. Am. J. 57, 1071–1076.

Campbell, C.A., Souster, W., 1982. Loss of organic matter and potentially mineralizable nitrogen from Saskatchewan soils due to cropping. Can. J. Soil Sci. 62, 651–656.

Dalal, R.C., Mayer, R.J., 1986. Long-term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. II. Total organic carbon and its rate of loss from the soil profile. Aust. J. Soil Res. 24, 281–292.

Doran, J.W., 1987. Microbial biomass and mineralizable nitrogen distributions in no-tillage and plowed soils. Biol. Fert. Soils 5, 68–75.

Doran, J.W., Parkin, T.B., 1994. Defining and assessing soil quality. In: Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A. (Eds.), Defining Soil Quality for a Sustainable Environment. Special Publication No. 35. Soil Science Society of America, Madison, WI, pp. 3–21.

Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1995a. Soil organic carbon, microbial biomass and mineralizable carbon and nitrogen in sorghum. Soil Sci. Soc. Am. J. 59, 460–466.

Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1995b. Tillage and crop effects on seasonal soil carbon and nitrogen dynamics. Soil Sci. Soc. Am. J. 59, 1618–1624.

Franzluebbers, A.J., Langdale, G.W., Schomberg, H.H., 1999. Soil carbon, nitrogen, and aggregation in response to type and frequency of tillage. Soil Sci. Soc. Am. J. 63, 349–355.

Gregorich, E.G., Ellert, B.H., Drury, C.F., Liang, B.C., 1996. Fertilization effects on soil organic matter turnover and corn residue C storage. Soil Sci. Soc. Am. J. 60, 472–476.

Hargrove, W.L., 1986. Winter legumes as a nitrogen source for no-till grain sorghum. Agron. J. 78, 70–74.

Havlin, J.L., Kissel, D.E., Maddux, L.D., Claasen, M.M., Long, J.H., 1990. Crop rotation and tillage effects on soil organic carbon and nitrogen. Soil Sci. Soc. Am. J. 54, 448–452.

Kuo, S., Sainju, U.M., Jellum, E.J., 1997a. Winter cover crop effects on soil organic carbon and carbohydrate. Soil Sci. Soc. Am. J. 61, 145–152.

Kuo, S., Sainju, U.M., Jellum, E.J., 1997b. Winter cover cropping influence on nitrogen in soil. Soil Sci. Soc. Am. J. 61, 1392–1399.

Lal, R., Kimble, J., 1997. Conservation tillage for carbon sequestration. Nutr. Cycl. Agroecosyst. 49, 243–253.

Liang, B.C., Mackenzie, A.F., 1992. Changes in soil organic carbon and nitrogen after six years of corn production. Soil Sci. 153, 307–313.

McGill, W.B., Cole, C.V., 1981. Comparative aspects of cycling of organic C, N, S, and P through soil organic matter. Geoderma 2, 267–286.

McVay, K.A., Radcliffe, D.E., Hargrove, W.L., 1989. Winter legume effects on soil properties and nitrogen fertilizer requirements. Soil Sci. Soc. Am. J. 53, 1856–1862.

Mulvaney, R.L., 1996. Nitrogen-inorganic forms. In: Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnson, C.T., Sumner, M.E. (Eds.), Methods of Soil Analysis. Part 3. Chemical Methods. SSSA Book Series, Vol. 5. Soil Science Society of America, Madison, WI, pp. 1123–1184.

Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. In: Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnson, C.T., Sumner, M.E. (Eds.), Methods of Soil Analysis. Part 3. Chemical Methods. SSSA Book Series, Vol. 5. Soil Science Society of America, Madison, WI, pp. 961–1010.

Omay, A.B., Rice, C.W., Maddux, L.D., Gordon, W.B., 1997. Changes in soil microbial and chemical properties under long-term crop rotation and fertilization. Soil Sci. Soc. Am. J. 61, 1672–1678.

Paustian, K., Parton, W.J., Persson, J., 1992. Modeling soil organic matter in organic-amended and nitrogen-fertilized long-term plots. Soil Sci. Soc. Am. J. 56, 476–488.

Paustian, K., Andren, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noordwijk, M., Woomer, P.L., 1997. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use Manage. 13, 230–244.

Sainju, U.M., Good, R.E., 1993. Vertical root distribution in relation to soil properties in New Jersey Pinelands forest. Plant Soil 150, 87–97.

Sainju, U.M., Kalisz, P.J., 1990. Characteristics of ''coal bloom'' horizons in undisturbed forest soils in eastern Kentucky. Soil Sci. Soc. Am. J. 54, 879–882.

Salinas-Garcia, J.R., Hons, F.M., Matocha, J.E., 1997. Long-term effects of tillage and fertilization on soil organic matter dynamics. Soil Sci. Soc. Am. J. 61, 152–159.

SAS Institute, 1987. SAS System for Personal Computers, Version 6.04. SAS Institute, Inc., Cary, NC.

Uhlen, G., 1991. Long-term effects of fertilizers, manures, straw, and crop rotation on total N and total C in soil. Acta Agric. Scand. 41, 119–127.

University of Georgia, 1995. Commercial tomato production and management. Bulletin No. 1116. Cooperative Extension Service, University of Georgia, Athens, GA, p. 16.