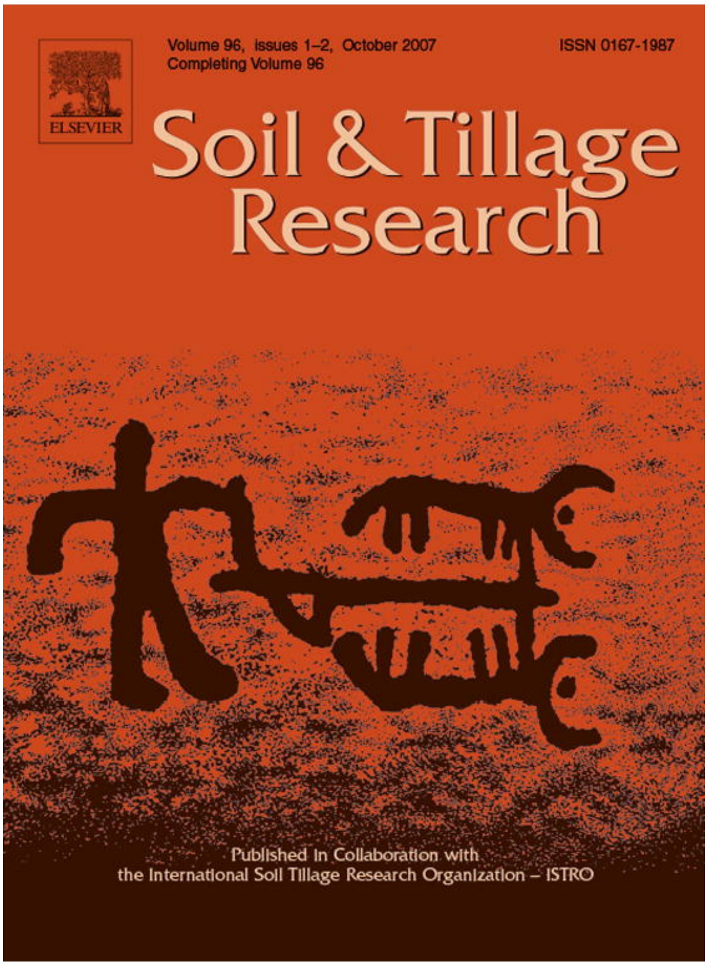
Volume 96, Issues 1–2, October 2007
Completing Volume 96
ISSN 0167-1987
ELSEVIER
Soil & Tillage Research
Published in Collaboration with
the International Soil Tillage Research Organization – ISTRO

Available online at www.sciencedirect.com
ScienceDirect
Soil & Tillage Research 96 (2007) 205–218
Soil & Tillage Research
www.elsevier.com/locate/still

Cover crop effect on soil carbon fractions under conservation tillage cotton

Upendra M. Sainju [a,*], Harry H. Schomberg [b], Bharat P. Singh [c], Wayne F. Whitehead [c], P. Glynn Tillman [d], Sharon L. Lachnicht-Weyers [e]

[a] USDA-ARS, 1500 North Central Avenue, Sidney, MT 59270, USA
[b] USDA-ARS, 1420 Experimental Station Road, Watkinsville, GA 30677, USA
[c] Agricultural Experiment Station, Fort Valley State University, Fort Valley, GA 31030, USA
[d] USDA-ARS, Crop Protection & Management Research Laboratory, Tifton, GA 31793, USA
[e] USDA-ARS, North Central Soil Conservation Research Laboratory, Morris, MN 56267, USA

Received 11 September 2006; received in revised form 21 March 2007; accepted 6 June 2007

Abstract

Cover crops may influence soil carbon (C) sequestration and microbial biomass and activities by providing additional residue C to soil. We examined the influence of legume [crimson clover (*Trifolium incarnatum* L.)], nonlegume [rye (*Secale cereale* L.)], blend [a mixture of legumes containing balansa clover (*Trifolium michelianum* Savi), hairy vetch (*Vicia villosa* Roth), and crimson clover], and rye + blend mixture cover crops on soil C fractions at the 0–150 mm depth from 2001 to 2003. Active fractions of soil C included potential C mineralization (PCM) and microbial biomass C (MBC) and slow fraction as soil organic C (SOC). Experiments were conducted in Dothan sandy loam (fine-loamy, kaolinitic, thermic, Plinthic Kandiudults) under dryland cotton (*Gossypium hirsutum* L.) in central Georgia and in Tifton loamy sand (fine-loamy, siliceous, thermic, Plinthic Kandiudults) under irrigated cotton in southern Georgia, USA. Both dryland and irrigated cotton were planted in strip tillage system where planting rows were tilled, thereby leaving the areas between rows untilled. Total aboveground cover crop and cotton C in dryland and irrigated conditions were 0.72–2.90 Mg C ha^{-1} greater in rye + blend than in other cover crops in 2001 but was 1.15–2.24 Mg C ha^{-1} greater in rye than in blend and rye + blend in 2002. In dryland cotton, PCM at 50–150 mm was greater in June 2001 and 2002 than in January 2003 but MBC at 0–150 mm was greater in January 2003 than in June 2001. In irrigated cotton, SOC at 0–150 mm was greater with rye + blend than with crimson clover and at 0–50 mm was greater in March than in December 2002. The PCM at 0–50 and 0–150 mm was greater with blend and crimson clover than with rye in April 2001 and was greater with crimson clover than with rye and rye + blend in March 2002. The MBC at 0–50 mm was greater with rye than with blend and crimson clover in April 2001 and was greater with rye, blend, and rye + blend than with crimson clover in March 2002. As a result, PCM decreased by 21–24 g CO_2–C ha^{-1} d^{-1} but MBC increased by 90–224 g CO_2–C ha^{-1} d^{-1} from June 2001 to January 2003 in dryland cotton. In irrigated cotton, SOC decreased by 0.1–1.1 kg C ha^{-1} d^{-1}, and PCM decreased by 10 g CO_2–C ha^{-1} d^{-1} with rye to 79 g CO_2–C ha^{-1} d^{-1} with blend, but MBC increased by 13 g CO_2–C ha^{-1} d^{-1} with blend to 120 g CO_2–C ha^{-1} d^{-1} with crimson clover from April 2001 to December 2002. Soil active C fractions varied between seasons due to differences in temperature, water content, and substrate availability in dryland cotton, regardless of cover crops. In irrigated cotton, increase in crop C input with legume + nonlegume treatment increased soil C storage and microbial biomass but lower C/N ratio of legume cover crops increased C mineralization and microbial activities in the spring.
Published by Elsevier B.V.

Keywords: Cover crop; Organic carbon; Microbial carbon; Carbon mineralization; On-farm study; Soil quality; Cropping system

* Corresponding author. Tel.: +1 406 433 9498; fax: +1 406 433 5038.
E-mail address: usainju@sidney.ars.usda.gov (U.M. Sainju).

0167-1987/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.still.2007.06.006

1. Introduction

Soils in the humid region of the Southeastern USA have lower organic matter levels than in the temperate regions due to greater rates of mineralization and severe erosion as a result of a long history of intensive cultivation (Langdale et al., 1991; Allmaras et al., 2000; Franzluebbers and Steudemann, 2003). The mild winter of this region is favorable for growing cover crops which increase C inputs and soil organic matter compared with bare fallow (McVay et al., 1989; Schomberg and Endale, 2004; Sainju et al., 2006). Combined with conservation tillage, cover crops have been shown to improve the productivity of degraded soils in the Southeastern USA (Bruce et al., 1995; Sainju et al., 2002). While nonlegume cover crops are effective in capturing soil residual N left after crop harvest in the autumn and reducing N leaching compared with legumes or no cover crop, legumes can increase N supply and reduce the amount of N fertilizer required for succeeding summer crops (Meisinger et al., 1991; McCracken et al., 1994; Kuo et al., 1997b). A mixture of legume and nonlegume cover crops could be more ideal for supplying both C and N inputs in adequate amounts that help to improve soil quality and productivity by increasing organic matter and reducing the potential for N leaching than the individual species.

Although soil organic C (SOC) is an important component of soil quality and productivity, because of its large pool size and inherent spatial variability, measurement of SOC alone does not adequately reflect changes in soil quality and nutrient status (Franzluebbers et al., 1995; Bezdicek et al., 1996). Measurement of biologically active fractions of SOC that change rapidly over time, such as microbial biomass C (MBC) and potential C mineralization (PCM), could better reflect changes in soil quality and nutrient dynamics (Saffigna et al., 1989; Bremner and Van Kissel, 1992) due to changes induced by crop management practices, such as cover cropping (Mendes et al., 1999; Schutter and Dick, 2002). Sainju et al. (2003) reported that rye increased MBC and PCM compared with hairy vetch, crimson clover, or no cover crop due to greater biomass yield and C content. Mendes et al. (1999) found that MBC was greater with cover crops than with bare fallow in September 1995 but was similar between treatments in June and September 1996. In contrast, PCM was greater with cover crops than with fallow in June and September 1996. Similarly, Schutter and Dick (2002) reported that MBC increased from March to August 1998 with cover crops but decreased with fallow. On the other hand, PCM decreased from March to August 1998, regardless of cover crop treatment. The seasonal variations in MBC and PCM levels between cover crop and fallow treatments had been attributed to differences in nutrient levels, substrate availability, and soil temperature and water content (Miller and Dick, 1995; Schutter and Dick, 2002). In red clay soils in Australia, Blair and Crocker (2000) and Blair et al. (1998) found that wheat-legumes rotation increased labile C fractions but no effect on total C compared with continuous wheat.

Information on the effects of legume and nonlegume cover crops on soil labile and nonlabile C fractions is available but little is known about the effect of mixture of legume and nonlegume cover crops compared with either species alone or no cover crop on C fractions. Sainju et al. (2005b, 2006) reported that biculture of hairy vetch and rye increased crop biomass C and SOC compared with monoculture of either species or no cover crop. Cover crop mixtures can enhance soil productivity by building active organic matter pools and increasing N mineralization due to their large biomass production compared with individual species (Mutch and Martin, 1998). We hypothesized that MBC and PCM would be better responsive indicators of changes in soil organic matter due to cover crop management than SOC and that legume and nonlegume cover crop mixtures would result in greater levels of soil C fractions than either species alone or the no cover crop treatment due to increased amount of residue C returned to the soil. Our objectives were to: (1) examine the amount of cover crop and cotton biomass (stems + leaves) residue C returned to the soil from 2001 to 2002 in producers' field and (2) determine the effects of mono- and multiculture cover crops on the concentrations and contents of SOC, MBC, and PCM from 2000 to 2002 under dryland and irrigated conservation tillage cotton in the Southeastern USA.

2. Materials and methods

2.1. Experimental sites

The experiment was conducted from 2001 to 2003 at three producers' field sites near Bartow in central Georgia and at two sites near Tifton in southern Georgia, USA (Fig. 1, Table 1). The experimental sites contained nearly similar soil types and cropping systems. In both Tifton and Bartow, farms were considered as replications. At all sites, a WAS GPS system (and flagging) was used to reference sample locations so that subsequent samples (plant and soil)

Fig. 1. Location of experimental sites (indicated by stars) in Bartow and Tifton in the State of Georgia, USA.

were collected within 1 m of the original samples. In Bartow, four cover crop treatments (described below) were established on a contiguous 16 ha block in each farm with each treatment being established on a 4 ha area within the 16 ha block. Within each treatment, four zones were randomly designated for soil and plant sampling (A, B, C, and D). In Tifton, treatments were established in a 4 ha block within a larger field (10–20 ha). Treatments were applied to adjacent fields that were separated by a road or tree-lined area. Within each treatment, four zones were randomly designated for soil and plant sampling similar to those collected in Bartow (A, B, C, and D).

2.2. *Cover crop and cotton management*

Cover crop treatments consisted of rye (*Secale cereale* L.), blend [a mixture of legumes containing balansa clover (*Trifolium michelianum* Savi), hairy vetch (*Vicia villosa* Roth), and crimson clover (*Trifolium incarnatum* L.)], rye + blend mixture, and no cover crop in Bartow. In Tifton, treatments were rye, blend, rye + blend, and crimson clover. These differences were due to producer's choice and space allocation in the two locations. Cover crop mixtures were designed to improve the availability of food sources to beneficial insects (Tillman et al., 2004) and to increase biomass production for improving soil organic matter (Sainju et al., 2005b, 2006).

The dates for cover crop and cotton (*Gossypium hirsutum* L.) planting, biomass collection, and cotton lint harvest in Bartow and Tifton are shown in Table 1.

Table 1
Description of the experimental sites and crop and soil management in dryland cotton in Bartow and irrigated cotton in Tifton, Georgia

Description	Bartow	Tifton
Location	Central Georgia	Southern Georgia
Farms	Williams, Evans, and Harrison	Branch and Thompson
Soil type	Dothan sandy loam (fine-loamy, kaolinitic, thermic, Plinthic, Kandiudults)[a]	Tifton loamy sand (fine-loamy, siliceous, thermic, Plinthic, Kandiudults)[a]
Soil pH	6.0–6.5	6.0–6.7
Sand (g kg^{-1} soil)	650	750
Silt (g kg^{-1} soil)	250	160
Clay (g kg^{-1} soil)	100	90
Organic C (Mg C ha^{-1})	18.0	17.6
Previous crops	Continuous cotton (*G. hirsutum* L.)	Cotton-cotton-peanut (*Arachis hypogaea* L.)
Cover crops	Rye, blend[b], rye + blend, no cover crop[c]	Rye, blend, rye + blend, crimson clover
Cover crop planting	5–12 December 2000, 28 November–10 December 2001	13–20 December 2000, 11–21 December 2001
Cover crop biomass sampling	16–28 April 2001, 4–23 April 2002	29 April–11 May 2001, 24 April–11 May 2002
Cotton planting	1–15 May 2001, 26 April–3 May 2002	16–30 May 2001, 4–21 May 2002
Cotton biomass sampling	25–30 July 2001, 28 July–2 August 2002	31 July–5 August 2001, 3–7 August 2002
Cotton lint harvest	16–24 October 2001, 10–31 October 2002	25 October–3 December 2001, 1–21 November 2002
Soil sample collection	June 2001, June 2002, January 2003	April 2001, March 2002, December 2002

[a] USDA-SCS (1980).
[b] Blend is the mixture of legume cover crops containing balansa clover, crimson clover, and hairy vetch.
[c] No cover crop treatment contained biomass of winter weeds and their C and N contents.

Planting and harvest of cover crops and cotton were carried out by 1–2 weeks earlier in Bartow than in Tifton in order to account for the better use of soil temperature and water, especially for the dryland cropping system in Bartow, so that plant growth would not be severely affected. The planting and harvest dates for cover crops and cotton were similar to those used by producers in each location. Cover crops were planted with a no-till grain drill (Deere and CO., Moline, IL) in the same place in each year to examine their long-term influence on soil C fractions. Rye was seeded at 56 kg ha^{-1} and crimson clover at 17 kg ha^{-1} with 0.18 m row spacing. For blend, balansa clover was seeded at 2 kg ha^{-1}, crimson clover at 6 kg ha^{-1}, and hairy vetch at 11 kg ha^{-1}. For rye + blend mixture, rye and blend were seeded at above seeding rates in alternate strips of 0.46 m wide to accommodate cotton planting in rye rows. Legume cover crops were inoculated with proper *Rhizobium* species before planting.

Cover crop biomass samples were collected from two 1 m^2 areas in each A, B, C, and D zones within each treatment and weighed. Biomass samples were collected within 3 m of locations used to collect soil samples. Samples from each zone within a treatment were composited and weighed, after which a subsample of 2 kg was collected to determine dry matter yield and C and N concentrations. 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. Subsamples were oven-dried at 60 °C for 3 d, weighed, and ground in a Wiley-mill to pass a 1-mm screen. After sampling, all cover crops, except rye, were killed in strips by applying appropriate herbicides to the row area where cotton would be planted. For the rye treatment, all plants were killed by spraying herbicide. Cover crops in the strip-killed areas continued to grow between cotton rows until the first application of glyphosate [*N*-(phosphonomethyl) glycine] at the 4–6 leaf stage of cotton growth. No attempt was made to measure the amount of cover crop biomass produced during the 3–5 weeks following the herbicide application.

At 10–20 d after killing cover crops, plots were tilled with strip-till rigs (Deere and CO., Moline, IL; KMC Inc., Tifton, GA) where in-row subsoiling in a narrow strip of 0.3 m width was done over the row to 0.35 m depth for planting cotton, thereby leaving the area between rows undisturbed. The surface-tilled zone was leveled by coulters behind the subsoiler. Glyphosate-resistant cotton [cv. DP458, DP5415, DP5690, and Delta Pearl (all from Delta and Pine Land CO, Scott, MS)] was planted at 11 kg ha^{-1} with the no-till planter (Deere and CO., Moline, IL) in 0.92 m rows. Cotton cultivars in each site was chosen based on their abilities to tolerate diseases and pests and produce sustainable cotton yields under dryland and irrigated conditions. Cotton was applied with appropriate rates of N, P, and K fertilizers, herbicides, and pesticides during their growth. Cotton in Bartow farms was not irrigated while that in Tifton farms was irrigated using sprinkler system based on producers' evaluation of water needs. Due to limited resources, we were not able to determine the amount of water applied to cotton in Tifton farms. However, for each farm in Tifton, the same farmer managed irrigation in all treatments near the same time based on the same schedule.

Cotton biomass (stems + leaves) was collected at the late bloom stage (Table 1) from two central rows (6.2 m × 1.8 m) after removing lint and seeds. A subsample (≈100 g) of the composited sample (after cutting to 2 cm pieces) was oven-dried at 60 °C for 3 d, weighed, and ground in a Wiley-mill to pass a 1-mm screen to determine C and N concentrations. After 10 weeks, cotton lint and seed were harvested from an area of 120 m × 150 m with a John Deere cotton picker (Deere and CO., Moline, IL). Cotton stalks were either pulled with a stalk puller or shredded with a mower following cotton harvest.

2.3. Soil sample collection and analysis

Soil samples were collected with a probe (50 mm inside diameter) by taking three cores from each zone (A, B, C, and D) for a total of 12 samples for each treatment. Samples were collected from the 0–150 mm depth at three dates in each location (Table 1). These were separated into 0–50 and 50–150 mm depths, composited within a depth, air-dried, and sieved to 2-mm. The bulk density of each soil layer was estimated from the depth, probe diameter, and soil mass for each sampling date.

The SOC concentration (g kg^{-1} soil) was determined by using the high induction furnace C and N analyzer (LECO, St. Joseph, MI). The PCM in air-dried soils was determined by the method modified by Haney et al. (2004). Twenty gram soil subsample was moistened with water at 50% field capacity and placed in a 1 L jar containing beakers with 4 mL of 0.5 M NaOH to trap evolved CO_2 and 20 mL of water to maintain high humidity. Soil was incubated in the jar at 21 °C for 10 d. At 10 d, the beaker containing NaOH was removed from the jar and PCM was determined by measuring

CO_2–C absorbed in NaOH, which was back-titrated with 1.5 M $BaCl_2$ and 0.1 M HCl.

The beaker containing moist soil and incubated for 10 d (used for PCM determination above) was continued to be used for determining MBC by the modified fumigation-incubation method for air-dried soils (Franzluebbers et al., 1996). The moist soil was fumigated with ethanol-free chloroform for 24 h and placed in a 1 L jar containing beakers with 4 mL of 0.5 M NaOH and 20 mL water. As with PCM, fumigated moist soil was incubated for 10 d and CO_2 absorbed in NaOH was back-titrated with $BaCl_2$ and HCl. The MBC was calculated by dividing the amount of CO_2–C absorbed in NaOH by a factor of 0.41 (Voroney and Paul, 1984) without subtracting the values from the nonfumigated control (Franzluebbers et al., 1996).

The contents (Mg ha^{-1} or kg ha^{-1}) of SOC, PCM, and MBC at 0–50 and 50–150 mm depths were calculated by multiplying their concentrations by bulk density and thickness of soil layer after using proper conversion units. The total contents at the 0–150 mm depth were determined by summing the contents at 0–50 and 50–150 mm.

Carbon and N concentrations (g kg^{-1}) in cover crop and cotton biomass were determined by using the C and N analyzer (LECO, St. Joseph, MI). Carbon contents (kg ha^{-1}) in cover crop and cotton biomass were calculated by multiplying their concentrations by biomass yields.

2.4. Data analysis

Data for cover crop and cotton biomass and their C and N contents in Bartow and Tifton farms were analyzed using the split-plot analysis in the MIXED procedure of SAS (Littell et al., 1996). Farms in each location were considered as replicates, cover crop as the main treatment, and year as the split-plot treatment. Treatments in these areas were arranged in a randomized block design. Fixed effects were cover crop and year and random effects were replication and cover crop × replication interaction. For SOC, PCM, and MBC, data were analyzed using the analysis of repeated measure in the MIXED procedure because these parameters were measured over time. Cover crop was considered as the main treatment and date of soil sampling as the repeated measure treatment. Means were separated by using the least square means test when treatments and interaction were significant. Statistical significance was evaluated at $P \leq 0.05$, unless otherwise stated.

3. Results and discussion

3.1. Cover crop and cotton carbon

Biomass yields and C contents in cover crops and cotton were lower in 2002 than in 2001 in both Bartow and Tifton farms (Table 2) due to a severe drought. The drought in 2002 started when rainfall in March (active cover crop growing month) was lower in 2002 (127–131 mm) than in 2001 (211–257 mm) (Table 3). Similarly, a limited rainfall of 15–59 mm occurred in June 2002 (active cotton growing month), which was well below the amount received in June 2001 (102–177 mm) and the 45-year average (102–113 mm). Furthermore, air temperature from March to October was higher in 2002 than in 2001 in both Bartow and Tifton, except in April, May, and August in Bartow (Table 3). The Tifton farms were irrigated during the cotton growing season based on producers' evaluation of water need. Even with irrigation, cotton biomass production was lower in 2002 than in 2001 (Table 3). Although cover crops were not irrigated, cover crop biomass and C contents were greater in Tifton than in Bartow, possibly due to greater soil water availability.

Biomass yield and C content in cover crops and cotton differed by cover crop species, years, and locations (Table 2). In Bartow, cover crop biomass yield and C content were greater in rye + blend than in other treatments but there were no residual influence on cotton biomass and C content among treatments in 2001. In 2002, cover crop biomass yield and C content were greater in rye and rye + blend than in blend and no cover crop. Cotton biomass and C content were greater following rye and no cover crop than following blend and rye + blend. In Tifton, cover crop biomass and C were greater in rye + blend than in other treatments but no residual effect of cover crops was observed on cotton biomass and C in 2001, a trend similar to that found in Bartow. In 2002, cover crop biomass and C were greater in rye than in other treatments. Cotton biomass and C were greater following rye than following blend. Total biomass C in cover crops and cotton returned to the soil were greater in rye + blend than in other treatments in 2001 and greater in rye than in blend and rye + blend in 2002 in both Bartow and Tifton (Table 2). The C/N ratio was lower for the residues of blend and crimson clover than for rye but C/N ratio in cotton residue was not influenced by cover crops. Although dates of planting and harvest for cover crops and cotton as well as cotton cultivars differed by 1–2 weeks among

Table 2
Effect of cover crops on biomass yields and C contents of cover crops and cotton in 2001 and 2002 in Bartow and Tifton, Georgia

Cover crop	Cover crop			Cotton			Total cover crop and cotton C content (Mg ha^{-1})
	Biomass yield (Mg ha^{-1})	C content (Mg ha^{-1})	C/N ratio	Biomass yield (Mg ha^{-1})	C content (Mg ha^{-1})	C/N ratio	
Bartow							
2001							
Rye	2.08(±0.17)[a] b[b]	0.91(±0.07) b	35(±4) a	6.46(±1.07) a	3.04(±0.32) a	23(±2) a	3.95(±0.47) b
Blend[c]	2.12(±0.27) b	0.89(±0.08) b	21(±3) c	7.37(±0.97) a	3.44(±0.39) a	21(±3) a	4.33(±0.53) b
Rye + blend	3.37(±0.25) a	1.51(±0.17) a	32(±4) ab	7.68(±1.17) a	3.54(±0.47) a	21(±2) a	5.05(±0.58) a
No cover crop[d]	0.93(±0.09) c	0.42(±0.05) c	28(±3) bc	6.55(±1.01) a	3.01(±0.27) a	21(±4) a	3.43(±0.57) c
2002							
Rye	1.90(±0.23) a	0.75(±0.05) a	17(±2) ab	5.44(±0.67) a	2.22(±0.32) a	15(±2) a	2.97(±0.37) a
Blend	0.95(±0.07) b	0.36(±0.04) b	12(±1) b	2.20(±0.23) b	0.85(±0.78) b	12(±2) a	1.21(±0.18) b
Rye + blend	1.96(±0.28) a	0.73(±0.07) a	14(±2) b	2.53(±0.37) b	0.96(±0.98) b	12(±3) a	1.69(±0.17) b
No cover crop	0.72(±0.05) b	0.28(±0.03) b	22(±3) a	6.28(±0.87) a	2.46(±0.33) a	15(±2) a	2.74(±0.38) a
Tifton							
2001							
Rye	5.35(±1.07) b[a]	2.35(±0.15) b	25(±3) a	12.05(±2.07) a	6.76(±1.27) a	26(±4) a	9.11(±1.31) b
Blend[b]	2.79(±0.37) c	1.11(±0.09) c	14(±1) b	12.83(±1.97) a	6.05(±1.03) a	26(±3) a	7.17(±1.07) c
Rye + blend	8.89(±1.73) a	3.70(±0.27) a	29(±3) a	14.88(±1.68) a	6.73(±0.77) a	26(±3) a	10.07(±2.07) a
Crimson clover	2.64(±0.37) c	1.14(±0.08) c	14(±2) b	13.56(±2.17) a	6.30(±0.71) a	24(±2) a	7.44(±0.79) c
2002							
Rye	2.79(±0.42) a	1.20(±0.03) a	22(±2) a	7.86(±0.75) a	3.52(±0.37) a	13(±2) a	4.72(±0.67) a
Blend	1.54(±0.24) b	0.56(±0.02) b	13(±2) b	4.60(±0.49) b	1.92(±0.18) b	12(±1) a	2.48(±0.35) c
Rye + blend	1.79(±0.17) b	0.68(±0.07) b	15(±1) b	6.50(±0.75) ab	2.90(±0.47) ab	15(±2) a	3.57(±0.48) b
Crimson clover	1.66(±0.13) b	0.69(±0.06) b	12(±2) b	5.81(±0.57) ab	2.53(±0.27) ab	13(±1) a	3.22(±0.42) b

[a] Value in the parenthesis is the standard deviation of the mean.
[b] Numbers followed by different letters within a column in a year are significantly different at $P \leq 0.05$ by the least square means test.
[c] Blend is the mixture of legume cover crops containing balansa clover, crimson clover, and hairy vetch.
[d] No cover crop treatment contained biomass of winter weeds and their C and N contents.

farms and locations (Table 1), these were chosen to adopt crops in the particular soil and environmental conditions at each site and to produce sustainable yields. Therefore, it is expected that these factors will have minimum impacts on crop biomass C production and soil C fractions.

In both locations, rye and rye + blend were superior biomass producing cover crops. Even though biomass production in 2002 decreased due to significant drought experienced in the Southeastern USA, rye provided enough biomass at all farms to provide more than 30% cover at cotton planting. Superior performance of rye on biomass production in the Southeastern USA has been observed in other conservation tillage studies (Sainju et al., 2005a; Schomberg et al., 2006). Based on biomass production and C contents (Table 2), rye and rye + blend would be better cover crop choices in a normal growing season in the Southeastern USA. As a result, both biomass production and C/N ratio of crop residues are expected to influence differentially on soil C fractions.

3.2. Soil bulk density

Soil bulk density was not significantly influenced by cover crop, date of sampling, and soil depth in Bartow (Table 4). In Tifton, bulk density varied with cover crops but not with date of sampling and its interaction with cover crop. Averaged across sampling dates, bulk density was higher with rye + blend and crimson clover than with blend at 0–50 mm and higher with rye and rye + blend than with blend at 50–150 mm. Appropriate bulk density values for each cover crop and soil depth were used to convert concentrations (g kg^{-1}) of C fractions to contents (kg ha^{-1}).

3.3. Soil carbon fractions

3.3.1. Bartow

Differences in C inputs among cover crop treatments did not influence concentrations and contents of SOC, PCM, and MBC in Bartow. Similarly, the interaction of cover crop and date of soil sampling was not significant

Table 3
Monthly average air temperature and total rainfall from 2001 to 2003 in Bartow and Tifton, Georgia

Month	Bartow				Tifton			
	2001	2002	2003	45-year average	2001	2002	2003	45-year average
Temperature (°C)								
January	7.9	9.9	6.5	7.9	8.6	11.4	7.4	9.8
February	12.7	9.1	10.0	9.7	14.5	10.5	11.4	11.2
March	12.8	15.4	15.3	13.7	13.8	16.1	16.6	14.5
April	18.7	21.0	17.6	17.9	19.2	21.6	19.0	18.7
May	22.6	22.2	22.5	22.0	22.8	23.0	23.7	22.7
June	25.5	26.4	25.4	25.3	25.5	26.2	25.9	25.8
July	26.8	28.1	26.5	26.8	27.0	28.0	26.6	26.8
August	27.3	27.1	26.9	26.2	26.7	27.2	26.9	26.7
September	23.1	25.5	23.4	23.6	23.4	26.3	24.0	24.6
October	17.4	20.3	18.8	18.3	18.1	21.7	19.9	19.5
November	16.5	12.1	15.3	13.5	17.6	13.3	16.5	14.4
December	12.1	8.0	7.1	9.1	13.4	9.7	8.7	10.6
Rainfall (mm)								
January	50	77	41	115	49	82	7	113
February	37	59	119	100	16	42	107	103
March	211	127	215	120	257	131	209	129
April	37	41	137	79	43	67	88	97
May	53	46	212	84	38	20	32	86
June	102	59	152	102	177	15	165	113
July	39	67	322	121	87	85	187	139
August	44	88	74	121	47	58	204	120
September	83	117	44	92	79	105	101	94
October	7	93	90	73	63	154	117	58
November	31	124	38	66	20	125	31	61
December	17	127	47	178	19	93	55	92
Total	710	1024	1490	1150	894	976	1304	1202

for these parameters. Averaged across cover crops and date of sampling, SOC concentrations at 0–50 and 50–150 mm were 14.7 and 9.9 g C kg^{-1} soil, respectively, and SOC contents at 0–50, 50–150, and 0–150 mm depths were 7.7, 10.8, and 18.5 Mg C ha^{-1}, respectively (Table 5). The concentration and content of PCM at 50–150 mm were significantly greater in June 2001 and 2002 than in January 2003. In contrast, the concentration and content of MBC at 0–50 mm were greater in January 2003 than in June 2001 and at 50–150 and 0–150 mm was greater in January 2003 than in June 2001 and 2002. From June 2001 to January 2003, PCM increased by 2 g CO_2–C ha^{-1} d^{-1} at 0–50 mm but decreased by 21–24 g CO_2–C ha^{-1} d^{-1} at 50–150 and

Table 4
Effect of cover crops on soil bulk density averaged across sampling dates in Bartow and Tifton, Georgia

Cover crop	Soil bulk density (Mg m^{-3}) at soil depth			
	Bartow		Tifton	
	0–50 mm	50–150 mm	0–50 mm	50–150 mm
Rye	1.08(±0.07)[a] a[b]	1.10(±0.01) a	1.03(±0.01) ab	1.01(±0.02) a
Blend[c]	1.05(±0.10) a	1.08(±0.07) a	0.95(±0.02) b	0.91(±0.05) b
Rye + blend	1.05(±0.10) a	1.10(±0.05) a	1.06(±0.05) a	1.00(±0.02) a
Crimson clover	–	–	1.06(±0.03) a	0.97(±0.01) ab
No cover crop[d]	1.06(±0.04) a	1.10(±0.05) a	–	–

[a] Value in the parenthesis is the standard deviation of the mean.
[b] Numbers followed by different letters within a column are significantly different at $P \leq 0.05$ by the least square means test.
[c] Blend is the mixture of legume cover crops containing balansa clover, crimson clover, and hairy vetch.
[d] No cover crop treatment contained winter weeds.

Table 5
Effect of date of soil sampling on concentrations and contents of soil organic C (SOC), potential C mineralization (PCM), and microbial biomass C (MBC) at 0–50, 50–150, and 0–150 mm depths averaged across cover crops in Bartow, Georgia

Parameter	Date of soil sampling		
	June 2001	June 2002	January 2003
SOC concentration (g C kg^{-1} soil)			
0–50 mm	13.8(±4.0)[a] a[b]	15.2(±5.1) a	15.2(±5.2) a
50–150 mm	9.4(±3.2) a	9.9(±3.1) a	10.5(±3.4) a
PCM concentration (mg CO_2–C kg^{-1} soil)			
0–50 mm	101(±22) a	98(±19) a	105(±33) a
50–150 mm	54(±7) a	51(±12) ab	41(±13) b
MBC concentration (mg CO_2–C kg^{-1} soil)			
0–50 mm	249(±71) b	298(±103) ab	350(±56) a
50–150 mm	123(±36) b	148(±39) b	199(±34) a
SOC content (Mg C ha^{-1})			
0–50 mm	7.2(±1.7a)	7.9(±2.2) a	7.9(±2.5) a
50–150 mm	10.4(±3.4a)	10.7(±3.0) a	11.4(±3.6) a
0–150 mm	17.6(±5.2) a	18.6(±5.0) a	19.3(±5.8) a
PCM content (kg CO_2–C ha^{-1})			
0–50 mm	53(±11) a	52(±9) a	55(±15) a
50–150 mm	59(±7) a	55(±12) a	44(±13) b
0–150 mm	112(±15) a	107(±17) a	99(±25) a
MBC content (kg CO_2–C ha^{-1})			
0–50 mm	130(±32) b	156(±48) ab	184(±23) a
50–150 mm	135(±39) b	161(±42) b	217(±36) a
0–150 mm	265(±64) b	317(±83) b	401(±45) a
PCM/SOC ratio (g kg^{-1} SOC)			
0–50 mm	7.5(±1.4) a	7.2(±2.8) a	7.1(1.2) a
50–150 mm	6.2(± 1.7) a	5.6(±2.1) a	4.0(±0.9) b
0–150 mm	6.8(±1.6) a	6.2(±2.3) a	5.3(±0.9) a
MBC/SOC ratio (g kg^{-1} SOC)			
0–50 mm	18.2(±1.9) b	20.3(±5.5) ab	24.9(±6.5) a
50–150 mm	13.4(±1.9) b	15.7(±4.0) b	20.3(±5.5) a
0–150 mm	15.4(±1.6) b	17.6(±4.3) b	22.1(±5.5) a
PCM/MBC ratio (g kg^{-1} MBC)			
0–50 mm	415(±71) a	358(±116) ab	294(±65) b
50–150 mm	467(±111) a	360(±121) b	204(±48) c
0–150 mm	438(±84) a	354(±95) b	245(±51) c

[a] Value in parenthesis is the standard deviation of the mean.
[b] Numbers followed by different letters within a row are significantly different at $P \leq 0.05$ by the least square means test.

0–150 mm (Table 6). Similarly, MBC increased by 90–225 g CO_2–C ha^{-1} d^{-1} at 0–50, 50–150, and 0–150 mm.

The lack of differences in soil C fractions among cover crop treatments suggests that 2 years of C inputs were not sufficient to influence soil C dynamics under dryland conservation tillage practice in central Georgia, even though the amount of C input varied between treatments (Table 2). This indicates that limited soil water content under dryland cotton reduced mineralization of plant C and its turnover rate to soil C. As a result, it would take more than 2 years to observe changes in soil C fractions under dryland cotton as influenced by cover crops. Since soils were sampled at 7–12 months intervals, it could be possible that sampling at shorter intervals could have detected more readily the effect of cover crops on soil C fractions, especially the active fractions. As expected, date of soil sampling had a greater influence on active than on slow C fractions. The lower PCM in January 2003 than in June 2001 and 2002 might be a result of changes in the availability of mineralizable substrate and decreased microbial activities due to reduced temperature (Table 3) and nutrient availability. Schutter and Dick (2002) found that PCM decreased from March to August 1998 due to decreased N availability. In contrast, increased MBC in January 2003 compared with June 2001 and 2002 may be related to improved soil moisture conditions in November and December 2002 due to increased rainfall. The monthly total rainfall in November and December was 93–110 mm higher in 2002 than in 2001 (Table 3). In contrast, monthly air temperature in January was 1.4–3.4 °C lower in 2003 than in 2001 and 2002. It could be possible that greater C input from cotton in November and December than from cover crops in April 2002

Table 6
Effect of cover crops on the rate of change of soil organic C (SOC), potential C mineralization (PCM), and microbial biomass C (MBC) in Bartow and Tifton, Georgia

Parameter	Rate of change of C fractions at soil depth		
	0–50 mm	50–150 mm	0–150 mm
Bartow			
PCM (g CO_2–C ha^{-1} d^{-1})	2	−24	−21
MBC (g CO_2–C ha^{-1} d^{-1})	90	134	225
Tifton			
SOC (kg C ha^{-1} d^{-1})	−0.1	−0.1	−1.1
PCM (g CO_2–C ha^{-1} d^{-1})			
Rye	−10	−24	−35
Blend[a]	−51	−28	−79
Rye + blend	−42	−27	−68
Crimson clover	−30	−33	−62
MBC (g CO_2–C ha^{-1} d^{-1})			
Rye	39	21	60
Blend	84	13	71
Rye + blend	20	35	16
Crimson clover	25	95	120

[a] Blend is the mixture of legume cover crops containing balansa clover, crimson clover, and hairy vetch test.

(Table 2) increased MBC in January 2003 due to increased turnover of plant C into soil microbial C as a result of increased soil moisture content in November and December 2002. Consecutive addition of C from previous crop residues due to increased cropping intensity also could have increased MBC in January 2003 compared with June 2001 and 2002. Increased MBC from spring to autumn were also noted by several researchers (Mendes et al., 1999; Schutter and Dick, 2002). A stepwise regression analysis of soil C fractions with crop biomass C, air temperature, and rainfall, however, failed to show significant relationships among them. Nevertheless, the results showed that SOC changed little compared with PCM and MBC even after 2 years under dryland cotton. The SOC changes slowly but active C fractions vary seasonally due to the growth of plant roots and rhizosphere and variations in temperature and rainfall (Franzluebbers et al., 1994, 1995, 2003).

Because of rapid changes of PCM and MBC relative to SOC over time, the proportions of SOC in PCM and MBC, i.e. PCM/SOC and MBC/SOC ratios, were also influenced by date of soil sampling but the effect of cover crop and its interaction with date of sampling on these parameters were not significant (Table 5). The proportion of SOC as PCM ranged from 0.5% to 0.8% and the proportion of SOC as MBC ranged from 1.6% to 2.2%. Mendes et al. (1999) and Schutter and Dick (2002) found that, in Oregon, PCM/SOC ratio varied from 0.1% to 0.4% and MBC/SOC ratio varied from 0.7% to 1.9%, as PCM and MBC relative to SOC varied with cover crops and date of sampling. Averaged across treatments, the proportions of SOC as PCM and MBC were greater at 0–50 mm (7.2 and 21.1 g kg^{-1} SOC, respectively) than at 50–150 mm (5.3 and 16.5 g kg^{-1} SOC). These are similar to the findings of other researchers who have noted stratification of soil C fractions with depth in the conservation tillage system (Franzluebbers et al., 1994). Greater proportions of SOC as PCM and MBC have been suggested as indications of an enlarging pool of soil organic matter (Powlson et al., 1987). The proportions of SOC as PCM and MBC at 0–150 mm were in between those at 0–50 and 50–150 mm (Table 5).

The PCM/MBC ratio, i.e. the proportion of CO_2 respired by soil microorganisms, also varied with date of sampling (Table 5). The greater ratios in June 2001 and 2002 than in January 2003 was likely due to increased C mineralization relative to the growth of microbial population due to increased soil temperature and moisture content as a result of increased air temperature and rainfall (Table 4). Averaged across treatments, PCM/MBC ratio decreased from 356 g kg^{-1} MBC at 0–50 mm to 344 g kg^{-1} MBC at 50–150 mm, probably due to reduction in substrate availability with depth, a finding in contrast to that reported by Franzluebbers et al. (1994).

3.3.2. Tifton

Cover crop treatments had greater influence on soil C fractions under irrigated cotton in Tifton than under dryland cotton in Bartow as indicated by greater significant differences among treatments on SOC, PCM, and MBC at various sampling dates in Tifton (Tables 5 and 7). The concentration and content of PCM at 0–50 mm were greater with blend and rye + blend than with rye in April 2001 and greater with crimson clover than with rye and rye + blend in March 2002 (Table 7). Similarly, PCM content at 0–150 mm was greater with blend and crimson clover than with rye in April 2001 and greater with crimson clover than with rye and rye + blend in March 2002. The concentration and content of MBC at 0–50 mm were greater with rye than with blend and crimson clover in April 2001 and greater with rye, blend, and rye + blend than with crimson clover in March 2002 (Table 8). The PCM/SOC ratio at 0–50 mm was greater with blend and crimson clover than with rye and rye + blend in April 2001 and greater with crimson clover than with rye and rye + blend in March 2002 (Table 9). The MBC/SOC ratio at 0–50 and 0–150 mm was greater with rye than with blend in April 2001 and greater with rye than with crimson clover in March 2002. The PCM/MBC ratio at 0–50 and 0–150 mm was greater with blend and crimson clover than with rye in April 2001 and greater with crimson clover than with other cover crops in March 2002 (Table 10). Averaged across sampling dates, SOC concentration at 0–50 mm was greater with blend than with crimson clover but SOC content at 0–50 and 50–150 mm was greater with rye + blend than with crimson clover (Table 11). Averaged across cover crops, the concentration and content of SOC at 0–50 mm were greater in March than in December 2002. As a result, SOC decreased from 0.1 kg C ha^{-1} d^{-1} at 0–50 and 50–150 mm to 1.1 kg C ha^{-1} d^{-1} at 0–150 mm from April 2001 to December 2002 (Table 6). Similarly, PCM decreased from 10 g CO_2–C ha^{-1} d^{-1} with rye at 0–50 mm to 79 g CO_2–C ha^{-1} d^{-1} with blend at 0–150 mm. In contrast, MBC increased from 13 g CO_2–C ha^{-1} d^{-1} with blend at 50–150 mm to 120 g CO_2–C ha^{-1} d^{-1} with crimson clover at 0 ha^{-1} d^{-1}150 mm.

Differences in the quantity and quality (such as C/N ratio) of biomass residue between cover crop treatments influenced soil C fractions under irrigated cotton in

Table 7
Effect of cover crops on concentration and content of soil potential C mineralization (PCM) from April 2001 to December 2002 in Tifton, Georgia

Date of sampling	Cover crop	PCM concentration (mg CO_2–C kg^{-1} soil) at soil depth		PCM content (kg CO_2–C ha^{-1}) at soil depth		
		0–50 mm	50–150 mm	0–50 mm	50–150 mm	0–150 mm
April 2001	Rye	109(±19)[a]	67(±11)	56(±10)	68(±12)	124(±16)
	Blend[b]	179(±33)	84(±26)	85(±16)	75(±19)	161(±26)
	Rye + blend	155(±30)	77(±21)	73(±16)	76(±22)	149(±31)
	Crimson clover	138(±30)	79(±14)	82(±16)	78(±17)	160(±25)
March 2002	Rye	123(±23)	65(±8)	63(±12)	85(±9)	129(±18)
	Blend	149(±48)	76(±22)	70(±21)	69(±17)	139(±35)
	Rye + blend	123(±22)	63(±9)	63(±13)	62(±10)	125(±23)
	Crimson clover	154(±43)	84(±21)	81(±21)	80(±20)	161(±40)
December 2002	Rye	96(±30)	52(±6)	49(±15)	53(±6)	102(±29)
	Blend	113(±10)	65(±11)	54(±6)	59(±7)	113(±8)
	Rye + blend	107(±26)	62(±9)	58(±15)	64(±10)	121(±21)
	Crimson clover	101(±13)	57(±13)	54(±7)	58(±12)	111(±16)
LSD (0.05)[c]		30	–	16	–	26

[a] Value in parenthesis is the standard deviation of the mean.
[b] Blend is the mixture of legume cover crops containing balansa clover, crimson clover, and hairy vetch test.
[c] Least significant difference between treatments at $P = 0.05$.

Tifton. The greater SOC with rye + blend than with crimson clover (Table 11) may be attributed to increased biomass and C input from this treatment (Table 2). Sainju et al. (2006) reported a similar increase in soil C sequestration with rye + hairy vetch biculture compared with either of monocultures alone or no cover crop in a comparable soil series under irrigated cotton and sorghum in central Georgia due to increased C input. Similarly, greater MBC with rye and rye + blend than with crimson clover in April 2001 and March 2002 (Table 8) could be a result of greater C inputs from these treatments. Because of increased cover crop C, greater MBC with rye than with hairy vetch, crimson clover, or the no cover crop treatment under irrigated tomato in central Georgia were also noted by Sainju et al. (2000, 2003). In contrast, increased PCM with blend and

Table 8
Effect of cover crops on concentration and content of microbial biomass C (MBC) from April 2001 to December 2002 in Tifton, Georgia

Date of sampling	Cover crop	MBC concentration (mg CO_2–C kg^{-1} soil) at soil depth		MBC content (kg CO_2–C ha^{-1}) at soil depth		
		0–50 mm	50–150 mm	0–50 mm	50–150 mm	0–150 mm
April 2001	Rye	478(±37)[a]	226(±22)	228(±17)	229(±21)	457(±30)
	Blend[b]	337(±73)	225(±16)	175(±38)	205(±7)	380(±39)
	Rye + blend	369(±105)	207(±52)	200(±55)	210(±55)	412(±94)
	Crimson clover	329(±85)	198(±33)	181(±49)	199(±34)	383(±81)
March 2002	Rye	460(±129)	238(±60)	235(±64)	237(±23)	470(±120)
	Blend	484(±82)	258(±57)	230(±43)	235(±61)	464(±95)
	Rye + blend	450(±151)	245(±59)	231(±69)	240(±54)	469(±119)
	Crimson clover	329(±35)	230(±35)	166(±17)	217(±32)	380(±39)
December 2002	Rye	377(±91)	240(±45)	194(±45)	241(±43)	435(±39)
	Blend	366(±42)	232(±41)	194(±20)	210(±30)	384(±39)
	Rye + blend	340(±56)	227(±34)	181(±31)	228(±37)	409(±61)
	Crimson clover	360(±47)	257(±25)	191(±28)	253(±23)	444(±38)
LSD (0.05)[c]		120	–	44	–	–

[a] Value in parenthesis is the standard deviation of the mean.
[b] Blend is the mixture of legume cover crops containing balansa clover, crimson clover, and hairy vetch test.
[c] Least significant difference between treatments at $P = 0.05$.

Table 9
Effect of cover crops on the ratios of potential C mineralization (PCM)/soil organic C (SOC) and microbial biomass C (MBC)/SOC from April 2001 to December 2002 in Tifton, Georgia

Date of sampling	Cover crop	PCM/SOC (g kg^{-1} SOC) at soil depth			MBC/SOC (g kg^{-1} SOC) at soil depth		
		0–50 mm	50–150 mm	0–150 mm	0–50 mm	50–150 mm	0–150 mm
April 2001	Rye	7.9(±0.6)[a]	6.4(±1.2)	7.0(±0.8)	32.2(±2.9)	21.8(±3.5)	26.0(±2.8)
	Blend[b]	12.4(±2.7)	7.2(±1.7)	9.3(±1.6)	25.3(±6.2)	19.6(±1.6)	21.8(±2.7)
	Rye + blend	9.7(±2.5)	6.8(±1.4)	7.8(±1.6)	26.2(±1.8)	18.4(±3.2)	21.8(±4.8)
	Crimson clover	12.2(±1.9)	7.8(±1.1)	9.6(±1.1)	26.0(±5.1)	20.5(±5.9)	22.9(±5.3)
March 2002	Rye	8.8(±1.7)	6.6(±0.6)	7.5(±0.8)	33.0(±10.5)	24.1(±6.4)	27.7(±8.0)
	Blend	9.9(±3.3)	6.5(±1.5)	7.8(±2.0)	32.3(±5.9)	22.6(±6.4)	26.4(±5.6)
	Rye + blend	8.5(±1.4)	6.0(±1.0)	7.0(±0.9)	31.3(±9.4)	23.9(±7.8)	26.7(±7.9)
	Crimson clover	11.2(±3.3)	8.2(±1.3)	9.4(±1.8)	23.8(±4.7)	22.5(±2.0)	22.7(±1.8)
December 2002	Rye	7.5(±2.1)	8.0(±1.2)	5.9(±1.5)	29.3(±6.0)	22.8(±6.0)	25.2(±5.9)
	Blend	8.1(±1.0)	5.9(±0.8)	6.8(±0.6)	26.0(±3.6)	21.2(±2.4)	23.1(±2.2)
	Rye + blend	8.2(±1.5)	5.6(±0.7)	6.6(±0.7)	26.0(±4.2)	20.5(±2.1)	22.6(±2.4)
	Crimson clover	8.3(±1.1)	6.1(±1.2)	7.0(±1.1)	29.7(±2.3)	27.5(±2.6)	28.4(±2.3)
LSD (0.05)[c]		2.2	–	–	6.5	–	4.8

[a] Value in parenthesis is the standard deviation of the mean.
[b] Blend is the mixture of legume cover crops containing balansa clover, crimson clover, and hairy vetch test.
[c] Least significant difference between treatments at $P = 0.05$.

crimson clover compared with rye in April 2001 and March 2002 (Table 7) could be closely linked with C/N ratio of their residues. Both blend and crimson clover had significantly lower C/N ratio than rye (Table 2). As a result, blend and crimson clover residues may have mineralized more rapidly in the soil than rye residue, thereby increasing PCM. The greater rate of decrease of PCM and increase of MBC with blend and crimson clover than with rye (Table 6) also suggests that a greater turnover rate of cover crop C into active soil C fractions occurred with these treatments (Amado et al., 2006). The C/N ratio of cover crops can influence their mineralization rates (Kuo et al., 1997a,b; Sainju et al., 2000) and PCM (Sainju et al., 2003). While correlation between cover crop C and SOC and MBC was positive ($r = 0.59$–0.62, $P \leq 0.40$), significant negative

Table 10
Effect of cover crop on the ratio of potential C mineralization (PCM)/microbial biomass C from April 2001 to December 2002 in Tifton, Georgia

Date of sampling	Cover crop	PCM/MBC ratio (g kg^{-1} MBC) at soil depth		
		0–50 mm	50–150 mm	0–150 mm
April 2001	Rye	246(±45)[a]	290(±62)	271(±51)
	Blend[b]	486(±83)	360(±95)	424(±82)
	Rye + blend	365(±148)	351(±55)	362(±75)
	Crimson clover	453(±95)	399(±125)	418(±106)
March 2002	Rye	290(±99)	300(±95)	296(±96)
	Blend	321(±125)	319(±128)	319(±122)
	Rye + blend	304(±143)	288(±110)	295(±126)
	Crimson clover	480(±125)	376(±57)	421(±80)
December 2002	Rye	256(±40)	225(±42)	239(±40)
	Blend	315(±24)	282(±26)	298(±20)
	Rye + blend	324(±32)	281(±29)	301(±14)
	Crimson clover	288(±42)	226(±39)	254(±36)
LSD (0.05)[c]		100	–	82

[a] Value in parenthesis is the standard deviation of the mean.
[b] Blend is the mixture of legume cover crops containing balansa clover, crimson clover, and hairy vetch test.
[c] Least significant difference between treatments at $P = 0.05$.

Table 11
Effects of cover crops and date of soil sampling on concentration and content of soil organic C (SOC) in Tifton, Georgia

Treatment	SOC concentration (g C kg^{-1} soil) at soil depth		SOC content (kg C ha^{-1}) at soil depth		
	0–50 mm	50–150 mm	0–50 mm	50–150 mm	0–150 mm
Cover crop					
Rye	13.5(±1.5)[a] ab[b]	10.5(±2.1) a	7.0(±0.7) ab	10.6(±2.1) ab	17.6(±2.3) ab
Blend[c]	14.6(±0.8) a	11.4(±1.2) a	7.2(±0.4) ab	10.3(±0.8) ab	17.5(±0.8) ab
Rye + blend	13.8(±1.4) ab	11.0(±1.7) a	7.4(±0.8) a	11.0(±1.8) a	18.4(±2.4) a
Crimson clover	12.9(±1.4) b	9.9(±1.2) a	6.8(±0.8) b	9.6(±1.1) b	16.4(±1.5) b
Date of soil sampling					
April 2001	13.8(±1.4) ab	10.9(±1.5) a	7.1(±0.7) ab	10.6(±1.5) a	17.7(±2.0) a
March 2002	14.3(±1.1) a	10.5(±1.3) a	7.3(±0.5) a	10.2(±1.1) a	17.5(±1.2) a
December 2002	13.1(±1.4) b	10.6(±2.1) a	6.7(±0.7) b	10.3(±2.1) a	17.0(±2.5) a

[a] Value in parenthesis is the standard deviation of the mean.
[b] Numbers followed by different letter within a column of a set are significantly different at $P \leq 0.05$ by the least square means test.
[c] Blend is the mixture of legume cover crops containing balansa clover, crimson clover, and hairy vetch test.

correlation was observed between cover crop C/N ratio and PCM ($r = -0.91$, $P \leq 0.10$). Increase in SOC with increased plant C input has been known (Conteh et al., 1998; Hulugalle, 2000; Sherrod et al., 2005), but C mineralization as influenced by residue quality can have direct impact on nutrient availability, such as N, for crop production (Franzluebbers et al., 1994, 1995).

Similar trends in changes between PCM and PCM/SOC ratio and between MBC and MBC/SOC ratio as influenced by cover crops and date of soil sampling (Tables 7–9) indicate that both PCM and MBC are more sensitive to changes with crop management practices than SOC. Similarly, identical variations between PCM and PCM/MBC ratio suggest that PCM is even more sensitive to changes in crop management practices than MBC. The proportion of SOC in PCM ranged from 0.6% to 1.2% and the proportion of SOC in MBC ranged from 1.8% to 3.3%, which were slightly greater than the proportions found under dryland cotton in Bartow.

3.4. Comparison between locations

Comparison in changes in soil C fractions with identical cover crops (rye, blend, and rye + blend) and soil types between dryland and irrigated cotton in Bartow and Tifton, respectively, provides an opportunity to determine the influence of irrigation, temperature, and rainfall on soil C dynamics. While soil types were nearly identical, monthly average air temperature and total rainfall were slightly greater in Tifton than in Bartow (Tables 1 and 3). Increased rainfall and temperature can increase crop biomass yield and C input but increased soil temperature and water content can also increase C mineralization rate, thereby reducing the level of soil organic matter.

Considering that 1–2 weeks differences in cover crop and cotton planting, biomass collection, and lint harvest (Table 1) will not significantly influence C contribution from cover crop and cotton biomass between locations, biomass yields and C contents in cover crops and cotton were 0.9–2.6-fold greater in Tifton than in Bartow in 2001 and 2002 due increase in temperature and rainfall (Table 2) and difference in irrigated versus non-irrigated condition. As a result, total C input from cover crops and cotton was 1.6–2.3-fold greater in Tifton than in Bartow. While variations in active soil C fractions were largely seasonal in Bartow, greater level of C inputs and larger difference among cover crop treatments significantly influenced levels of C fractions over time in Tifton. Differences in soil water content and temperature were most likely the predominant factors affecting differences in plant C inputs, mineralization rates of soil and plant residue C, and soil organic matter levels under similar cover crops between the two locations. Marked difference in soil organic matter levels between locations as influenced by cover crops would be expected for periods longer than the present 2 years of study but significant differences in active C fractions can be found within a short period (Hulugalle et al., 1999; Mendes et al., 1999; Schutter and Dick, 2002; Sainju et al., 2003, 2006). However, irrigation can significantly influence soil C sequestration and microbial activities. Therefore, for examining the short-term benefits of cover crops on soil quality, active fractions of soil C are better response variables than slow fractions and that these benefits can be more readily obtained by growing cover crops in irrigated than in dryland cotton.

4. Conclusions

Changes in soil active and slow C fractions were differentially influenced by differences in rainfall, temperature, C inputs from cover crops and cotton biomass, residue C/N ratio, and soil water availability due to irrigated versus non-irrigated conditions between locations. In dryland cotton in Bartow, only seasonal variations in PCM and MBC occurred due to changes in temperature, rainfall, and substrate availability. In contrast, in irrigated cotton in Tifton, differences in C inputs and residue C/N ratio between cover crop treatments and seasonal variations in temperature and rainfall influenced SOC, PCM, and MBC levels. Greater C inputs with rye and rye + blend than with blend and crimson clover increased SOC and MBC. On the other hand, lower C/N ratio of blend and crimson clover than rye and rye + blend increased PCM in the spring. Active C fractions, such as PCM and MBC, measured changes in soil organic matter as influenced by crop management over time better than the slow fraction, such as SOC, when changes in its level were not detectable within a short period. Differences in soil water availability due to irrigated versus non-irrigated system not only produced different crop biomass yields and C inputs but also influenced C mineralization, microbial dynamics, and organic matter in comparable soils under conservation tillage cotton. Benefits of cover crops in increasing C sequestration and improving soil quality can be achieved more readily in irrigated than in dryland cotton.

Acknowledgements

The project was funded in part by a grant from USDA-southeast SARE. We acknowledge their financial support. We thank the producers, Frank Evans, Joe Harrison, Joe Williams at Bartow and Ryan Branch, Brian Ponder, and Grady Thompson at Tifton, GA for providing land and support for conducting this on-farm research.

References

Allmaras, R.R., Schomberg, H.H., Douglas, J., Dao, T.H., 2000. Soil organic carbon sequestration potential of adopting conservation tillage in U.S. croplands. J. Soil Water Conserv. 55, 365–373.

Amado, T.J.C., Bayer, C., Conceicao, P.C., Spagnollo, E., de Campos, B.C., da Veiga, M., 2006. Potential of carbon accumulation in no-till soils with intensive use and cover crops in southern Brazil. J. Environ. Qual. 35, 1599–1607.

Bezdicek, D.F., Papendick, R.I., Lal, R., 1996. Introduction: importance of soil quality to health and sustainable land management. In: Doran, J.W., Jones, A.J. (Eds.), Methods of Assessing Soil Quality. Soil Science Society of America, vol. 49. Spec. Publ, Madison, WI, pp. 1–18.

Blair, N., Crocker, G.J., 2000. Crop rotation effects on soil carbon and physical fertility of two Australian soils. Aust. J. Soil Res. 38, 71–84.

Blair, G.J., Chapman, L., Whitbread, A.M., Ball-Coelho, B., Larsen, P., Tiessen, H., 1998. Soil carbon changes resulting from sugarcane trash management at two locations in Queensland, Australia, and in northeast Brazil. Aust. J. Soil Res. 36, 873–882.

Bremner, E., Van Kissel, C., 1992. Plant-available nitrogen from lentil and wheat residues during a subsequent growing season. Soil Sci. Soc. Am. J. 56, 1155–1160.

Bruce, R.R., Langdale, G.W., West, L.T., Miller, W.P., 1995. Surface soil degradation and soil productivity restoration and maintenance. Soil Sci. Soc. Am. J. 59, 654–660.

Conteh, A., Blair, G.J., Rochester, I.J., 1998. Soil organic carbon fractions in a vertisol under irrigated cotton production as affected by burning and incorporating cotton stubble. Aust. J. Soil Res. 36, 655–668.

Franzluebbers, A.J., Steudemann, J.A., 2003. Bermuda grass management in southern Piedmont USA. III. Particulate and biologically active soil carbon. Soil Sci. Soc. Am. J. 67, 132–138.

Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1994. Long-term changes in soil carbon and nitrogen pools in wheat management systems. Soil Sci. Soc. Am. J. 58, 1639–1645.

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

Franzluebbers, A.J., Haney, R.L., Hons, F.M., Zuberer, D.A., 1996. Determination of microbial biomass and nitrogen mineralization following rewetting of dried soil. Soil Sci. Soc. Am. J. 60, 1133–1139.

Haney, R.L., Franzluebbers, A.J., Porter, E.B., Hons, F.M., Zuberer, D.A., 2004. Soil carbon and nitrogen mineralization: influence of drying temperature. Soil Sci. Soc. Am. J. 68, 489–492.

Hulugalle, N.R., 2000. Carbon sequestration in irrigated vertisols under cotton-based farming systems. Commun. Soil Sci. Plant Anal. 31, 645–654.

Hulugalle, Entwistle, P.C., Cooper, J.L., Scott, F., Nehl, D.B., Allen, S.J., Finlay, L.A., 1999. Sowing wheat or field pea as rotation crops after irrigated cotton in a grey vertisol. Aust. J. Soil Res. 37, 867–889.

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

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

Langdale, G.W., Blevins, R.L., Karlens, D.L., McCool, D.K., Nearing, M.A., Skidmore, E.L., Thomas, A.W., Tyler, D.D., Williams, J.R., 1991. Cover crop effects on soil erosion by wind and water. In: Hargrove, W.L. (Ed.), Cover Crops for Clean Water. Soil and Water Conservation Society, Ankeny, IA, pp. 15–22.

Littell, R.C., Milliken, G.A., Stroup, W.W., Wolfinger, R.D., 1996. SAS System for Mixed Models. SAS Inst Inc., Cary, NC.

McCracken, D.V., Smith, M.S., Grove, J.H., MacKown, C.T., Blevins, R.L., 1994. Nitrate leaching as influenced by cover cropping and nitrogen source. Soil Sci. Soc. Am. J. 58, 1476–1483.

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.

Meisinger, J.J., Hargrove, W.L., Mikkelsen Jr., R.I., Williams, J.R., Benson, V.W., 1991. Effects of cover crops on groundwater quality. In: Hargrove, W.L. (Ed.), Cover Crops for Clean Water. Soil and Water Conservation Society, Ankeny, IA, pp. 57–68.

Mendes, I.C., Bandick, A.K., Dick, R.P., Bottomley, P.J., 1999. Microbial biomass and activities in soil aggregates affected by winter cover crops. Soil Sci. Soc. Am. J. 63, 873–881.

Miller, M., Dick, R.P., 1995. Dynamics of soil C and microbial biomass on whole soil aggregates in two cropping systems differing in C-input. Appl. Soil Ecol. 2, 253–261.

Mutch, D.R., Martin, T.E., 1998. Cover crops. Michigan Field Crop Ecology. Managing Biological Processes for Productivity and Environmental Quality. Bull. E-2646. Michigan State Univ. Ext., East Lansing, MI.

Powlson, D.S., Brookes, P.C., Christensen, B.T., 1987. Measurement of soil microbial biomass provides an early indication of changes in total soil organic matter due to straw incorporation. Soil Biol. Biochem. 19, 159–164.

Saffigna, P.G., Powlson, D.S., Brookes, P.C., Thomas, G.A., 1989. Influence of sorghum residues and tillage on soil organic matter and soil microbial biomass in an Australian Vertisol. Soil Biol. Biochem. 21, 759–765.

Sainju, U.M., Singh, B.P., Whitehead, W.F., 2000. Cover crops and nitrogen fertilization effects on soil carbon and nitrogen and tomato yield. Can. J. Soil Sci. 80, 523–532.

Sainju, U.M., Singh, B.P., Whitehead, W.F., 2002. Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia. USA. Soil Tillage Res. 63, 167–179.

Sainju, U.M., Whitehead, W.F., Singh, B.P., 2003. Cover crops and nitrogen fertilization effects on soil aggregation and carbon and nitrogen pools. Can. J. Soil Sci. 83, 155–165.

Sainju, U.M., Singh, B.P., Whitehead, W.F., 2005a. Tillage, cover crops, and nitrogen fertilization effects on cotton and sorghum root biomass, carbon, and nitrogen. Agron. J. 97, 1279–1290.

Sainju, U.M., Whitehead, W.F., Singh, B.P., 2005b. Biculture legume-cereal cover crops for enhanced biomass yield and carbon and nitrogen. Agron. J. 97, 1402–1412.

Sainju, U.M., Singh, B.P., Whitehead, W.F., Wang, S., 2006. Carbon supply and storage in tilled and non-tilled soils as influenced by cover crops and nitrogen fertilization. J. Environ. Qual. 35, 1507–1517.

Schomberg, H.H., Endale, D.M., 2004. Cover crop effects on nitrogen mineralization and availability in conservation tillage cotton. Biol. Fertil. Soils 40, 398–405.

Schomberg, H.H., Endale, D.M., Calegari, A., Peixoto, R., Miyazawa, M., Cabrera, M.L., 2006. Influence of cover crops on potential nitrogen availability to succeeding crops in a Southern Piedmont soil. Biol. Fertil. Soils 42, 299–307.

Schutter, M.E., Dick, R.P., 2002. Microbial community profiles and activities among aggregates of winter fallow and cover-cropped soil. Soil Sci. Soc. Am. J. 66, 142–153.

Sherrod, L.A., Peterson, G.A., Westfall, D.G., Ahuja, L.R., 2005. Soil organic carbon pools after 12 years in no-till dryland agroecosystems. Soil Sci. Soc. Am. J. 69, 1600–1608.

Tillman, G., Schomberg, H.H., Phatak, S., Mullinix, B., Lachnicht, S., Timber, P., Olson, D., 2004. Influence of cover crops on insect pests and predators in conservation tillage cotton. J. Econ. Entomol. 97, 1217–1232.

United States Department of Agriculture, Soil Conservation Service (USDA-SCS), 1980. Soil Survey of Jefferson and Tift Counties, Georgia. United States Department of Agriculture, Washington, DC.

Voroney, R.P., Paul, E.A., 1984. Determination of k_C and k_N in situ for calibration of the chloroform fumigation-incubation method. Soil Biol. Biochem. 16, 9–14.