Impacts of landscape attributes on carbon sequestration during the transition from conventional to conservation management practices on a Coastal Plain field

J.A. Terra, D.W. Reeves, J.N. Shaw, and R.L. Raper

ABSTRACT: Field-scale experiments on degraded soils comparing management systems would facilitate a better understanding of the soil organic carbon (C) landscape dynamics associated with transition to conservation systems. We assessed the effects of soil management practices and terrain attributes on soil organic C in a 9 ha (22.2 ac) Alabama field (Typic and Aquic Paleudults). Treatments were established in strips across the landscape in a corn (*Zea mays* L.)-cotton (*Gossypium hirsutum* L.) rotation. Treatments included a conventional system (chisel plowing/disking without cover crops) with or without dairy manure, and a conservation system (no-till and cover crops) with and without manure. A soil survey, topography, soil electrical conductivity, initial soil organic C and soil texture were used to delineate management zones or clusters. After one rotation cycle (30 months), averaged across 240 positions distributed over the entire field, no-till or conventional tillage + manure increased soil organic C (0 to 5 cm; 0 to 2 in depth) by ~50 percent compared to conventional tillage (7.34 and 7.62 vs. 5.02 Mg ha^{-1}; 3.28 and 3.40 vs. 2.24 t ac^{-1}, respectively); but no-till+manure increased soil organic C by 157 percent. Initial soil organic C content was the most common correlated variable with soil organic C changes (ΔSOC) across the landscape for all treatments and conservation systems had greater soil organic C increases relative to conventional systems at low soil quality landscape positions. Our results show the potential to sequester C using high-residue producing conservation systems and manure is scale dependent, and may be higher than previously expected for degraded soils in the southeastern United States.

Keywords: Carbon sequestration, conservation systems, dairy manure, landscape variability, soil management, soil organic C, terrain attributes

Soils are major and active reservoirs to expand carbon (C) storage, despite doubts about their ability to mitigate climate change (Six et al., 2002). Although soil organic C changes related with management of agricultural soils were not explicitly included in the original Kyoto Protocol (Smith, 1999; Schlesinger, 2000), recent debates increased the likelihood that C storage in soils can be included in a national C budget (Pretty and Ball, 2001; Causarano, 2005). As a result, C trading and exchange systems are beginning to emerge and could represent an extra source of income for farmers. Moreover, due to additional benefits for soil quality, crop productivity and environmental quality, C sequestration holds the promise of bringing farmers a win-win option for managing soils wisely.

Soil organic C can be a sink or a source of carbon dioxide (CO_2), depending on land use and management. Long-term trials have demonstrated that continuous cropping with conventional tillage decreases soil organic C (Reeves, 1997). Sperow et al. (2003) estimated that U.S. croplands have 20 to 40 percent less C than uncultivated lands. However, under proper management, most agricultural soils can sequester C and improve soil quality (Reeves, 1997). Residue management, cover crops, crop rotations, no-till, and manure additions are known practices to increase soil organic C (Reeves, 1997; Batjes, 1998; Lal, 1997; Lal et al., 1998; Subak, 2000).

Soil management practices may help mitigate CO_2 emission and sequester C, allowing recovery in the next 50 years of about 50 to 70 percent of soil C losses since 1860 (Batjes, 1998). Conservation practices can sequester 0.5 to 1.0 Mg C ha^{-1} yr^{-1} (0.22 to 0.45 t C ac^{-1} yr^{-1}) in humid temperate regions, 0.2 to 0.5 Mg C ha^{-1} yr^{-1} (0.09 to 0.22 t C ac^{-1} yr^{-1}) in humid tropics and 0.1 to 0.2 Mg C ha^{-1} yr^{-1} (0.04 to 0.09 t C ac^{-1} yr^{-1}) in semi-arid zones (Subak, 2000; Robert, 2001). Long-term experiments have shown that no-till adoption and rotation changes can sequester 0.6 and 0.2 Mg C ha^{-1} yr^{-1} (0.27 to 0.09 t C ac^{-1} yr^{-1}), respectively (West and Post, 2002). A combination of practices, rather than an isolated one, is the best strategy for C sequestration (Paustian et al., 1997; Smith et al., 2000). Pretty and Ball (2001) reported that no-till can sequester 0.3 to 0.6 Mg C ha^{-1} yr^{-1} (0.13 to 0.27 t C ac^{-1} yr^{-1}), but combined with rotations and cover crops can build up 0.7 to 1.3 Mg C ha^{-1} yr^{-1} (0.31 to 0.58 t C ac^{-1} yr^{-1}). However, soil potential to sequester C is not unlimited (Post and Kwon, 2000; Smith et al., 2000). West and Post (2002) indicated that the C sequestration rate can be expected to peak in five to 10 years after a change from conventional tillage to no-till, with soil organic C reaching a new equilibrium in 15 to 20 years. Conversely, following initiation of an enhancement in rotation complexity, soil organic C may reach a new equilibrium in about 40 to 60 years.

Cotton monoculture and conventional tillage have been responsible for depleting C over decades in southern U.S. croplands. However, cotton integrated in cropping systems including rotations, cover crops and conservation tillage, dramatically reversed C depletion and increased C sequestration (Causarano et al., 2005). According to Eve et al. (2002), the southern United States is considered to have the second highest ability

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Journal of Soil and Water Conservation 60(6):438-446 www.swcs.org

Table 1. Application date, rate, amount and chemical composition of dairy bedding manure applied during three years on a 9-ha experiment in east central, Alabama. Applied rate, nutrients, and ash content are on a dry weight basis.

Application									
Date	Rate	C	N	P	K	Ca	Mg	Water	Ash
	Mg ha^{-1}	g kg^{-1}							
Feb. 2001	8.62	330	12.9	3.7	4.1	28.1	12.4	522	395
Nov. 2001	10.72	307	10.9	3.0	4.7	28.6	12.6	523	472
Aug. 2002	10.72	223	10.2	2.5	1.7	28.4	12.0	521	435

to sequester C in the country; only the Midwest has a higher ability to sequester C.

Quantification of original C stocks and their temporal change due to soil management are key tasks for estimating soil C sequestration. Historically, these estimations had been performed from data generated from small plots experiments. Because many soil properties linked with C sequestration vary significantly across space, quantitative assessment of soil quality and its relation to C sequestration is best achieved on a site-specific basis (Bergstrom et al., 2001; VandenBygaart et al., 2002). Spatial variation in soil organic C and its response to management is controlled by the combined influence of soil properties and terrain attributes on critical biological processes. Topography is related to soil organic C variability through its influence on soil properties, microbial activity, erosion and biomass production. Field water regime is highly dependent on terrain attributes that may influence soil C inputs and outputs through its effects on biomass production, soil organic C mineralization and erosion processes. VandenBygaart et al. (2002) established that landscape position and erosion deposition history were key factors in the ability of no-till soils to sequester C. Bergstrom et al. (2001) found that a no-till field had more soil organic C than a conventional tillage field, but only in well-drained upper slope positions. Field-scale experiments on degraded soils comparing management systems would facilitate a better understanding of soil organic C landscape dynamics associated with the transition to conservation tillage management.

The objective of this research was to determine the relative and interactive effects on soil organic C sequestration of four soil management practices with soil properties and terrain attribute variability on a coastal plain field in east-central Alabama.

Methods and Materials

Study location. A 9-ha (22.2 ac) field-scale study was conducted at the Alabama Agricultural Experiment Station's E.V. Smith Research Center in central Alabama (85°:53'50" W, 32°:25'22" N) from Oct 2000 to Mar 2003. Soils at the site are mostly fine and fine-loamy, siliceous, thermic Typic and Aquic Paleudults degraded from decades of sustained conventional tillage with row-crop monoculture. Initial soil analysis (0 to 30 cm depth; 12 in) indicated pH 6.5 (1:1 soil/water extract), and extractable phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) (Mehlich I) of 28, 96, 480 and 127 mg kg^{-1} (ppm) respectively.

Treatments, cultural practices, and experimental design. The field strip-trial was a factorial arrangement of two management systems with and without addition of dairy bedding manure in a corn-cotton rotation with both phases of the rotation present each year. Treatments were: 1) a conventional system (CT); 2) a conventional system + manure (CT+M); 3) a conservation system (NT); and 4) a conservation system + manure (no-till+M). The conventional system had no winter cover crops; tillage operations were performed in autumn (chisel plowing/disking), and in spring about two weeks prior to seeding (field cultivation and in-row subsoiling). The conservation system was no surface tillage with non-inversion in-row subsoiling and a winter cover crop mixture of white lupin (*Lupinus albus* L.), crimson clover (*Trifolium incarnatum* L.), and fodder radish (*Raphanus sativus* L.) prior to corn and a mixture of black oat (*Avena strigosa* Schreb.) and rye (*Secale cereale* L.) prior to cotton. After the 2002 growing season, sunn-hemp (*Crotalaria juncea* L.) was additionally included in the rotation sequence of the conservation systems between the corn and the rye-oat cover crop (September to November). Cover crops were killed two to three weeks before planting using glyphosate and a mechanical roller (Ashford and Reeves, 2003). In-row subsoiling at 0 to 40 cm depth (0 to 15.75 in) was performed with a KMC® subsoiler equipped with pneumatic rubber closing wheels (Kelly Manufacturing Co., Tifton, Georgia) prior to planting row crops. Dairy bedding manure was applied annually during autumn prior to the seeding of the winter cover crops at the assigned treatments (Table 1).

Treatments were in 6.1 m wide by ~240 m (20 by 790 ft) long strips across the landscape in a randomized complete block design with six replications. Cells of 6.1 by 18.3 m (20 by 60 ft) were delineated in each strip, resulting in a total of 496 cells for the entire field (Figure 1). Since both rotation phases were present each year, 50 percent of these cells were in cotton and 50 percent in corn. Cotton was seeded in six rows per strip at 165,000 seeds ha^{-1} (67,000 seeds ac^{-1}) in 102 cm (40 in) rows during the last week of May. Corn was seeded in eight rows per strip at 70,000 seeds ha^{-1} (28,000 seeds ac^{-1}) in 76 cm (30 in) rows during the first week of April. Nitrogen (NH_4NO_3) was broadcast at rates of 120 kg N ha^{-1} (107 lb N ac^{-1}) at planting in cotton, and at rates of 168 kg N ha^{-1} (150 lb N ac^{-1}) (1/3 at planting and 2/3 at V6-V8 stages) in corn. Other management practices for both crops followed Alabama Cooperative Extension System recommendations.

Data collection and measurements. An initial set of soil samples from the 496 cells was collected for baseline characterization data at the beginning of the test (fall 2000). In March 2003, after one rotation cycle (corn-cotton or cotton-corn, dependent on initiating crop phase per strip), 240 cells were sampled. At both times, core samples were collected to a depth of 30 cm (11.8 in) at 10 randomly selected points within each selected cell and composited; final core samples were sectioned into 0 to 5, 5 to 15, and 15 to 30 cm (0 to 2, 2 to 6, and 6 to 12 in) increments. All soil samples for C analysis were dried at 55° C (131° F), ground to a 2-mm (0.08 in) sieve and analyzed at once.

Seed cotton and grain corn yields were geo-referenced across the field in 2001 and 2002 seasons. The four center rows of each strip treatment were harvested using a spindle-picker or a combine equipped with a differential global positioning system (GPS) and yield monitors. The yield of each cell was calculated as the average of yield records

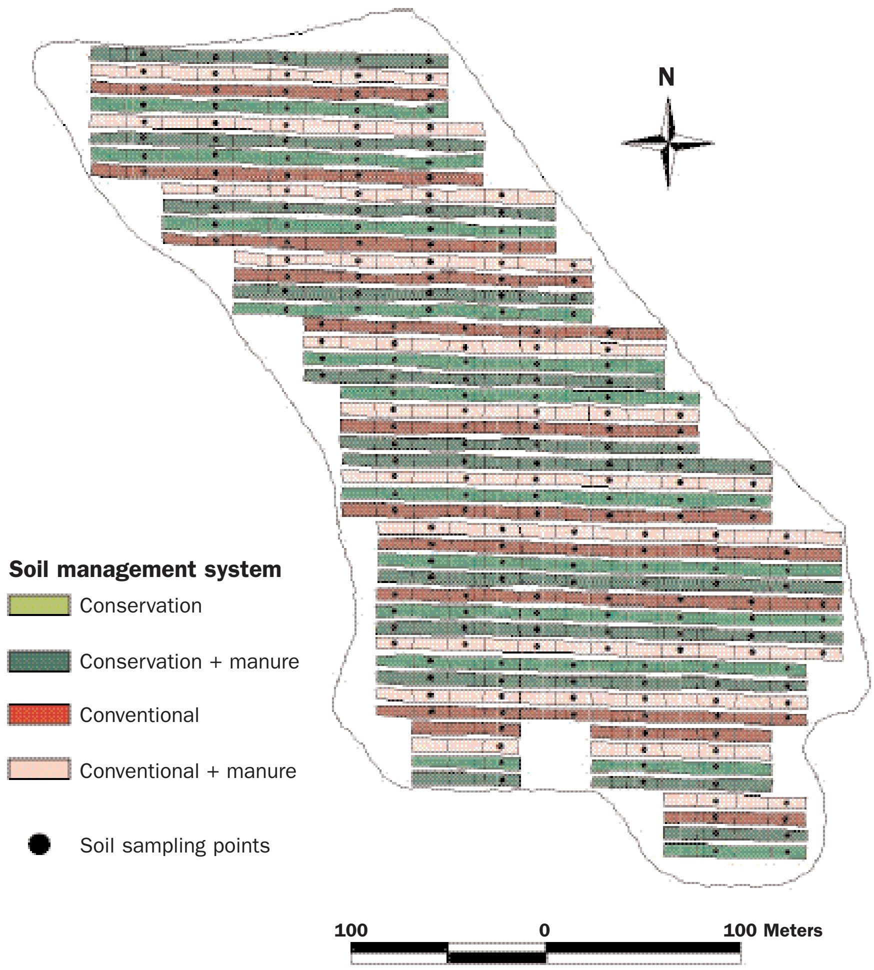


Figure 1
Layout of strip treatments and soil sampling sites disposition of a 9-ha field experiment in east-central Alabama (2001 to 2003).

within it. Residue biomass left on the soil surface by row crops, cover crops and weeds was determined in 2001 and 2002 to estimate C budgets across the field. Residue of row-crops was determined in 120 cells in each season as the mean of eight subsamples of 0.25-m^2 (2.7 ft^2). Cover crops and weed biomass were determined prior to termination in 240 cells each season as the mean of four subsamples of 0.25-m^2 (2.7 ft^2). Carbon content of soil samples and plant tissues was determined by dry combustion using a LECO® CN-2000 analyzer (Leco Corp., St. Joseph, Michigan).

Particle size distribution at 0 to 30 cm (0 to 12 in) was determined for 82 of the initial samples using the pipette method following organic matter removal (Kilmer and Alexander, 1949). A soil core sampler (5.3-cm diameter; 2 in) was used to determine soil bulk density (0 to 30 cm; 0 to 12 in) in 5-cm (2 in) increments. Bulk density was determined with three sub-samples per cell to allow volumetric computation of soil organic C (Mg SOC ha^{-1} ; t SOC ac^{-1}). Since the site had been managed uniformly with conventional tillage for decades, only 64 cells were sampled at the study's initiation. After three years of treatment imposition, 240 cells were sampled for bulk density determinations in 2003.

Landscape characterization. A detailed soil survey (scale ~1:5000) was developed according to National Cooperative Soil Survey standards. Seasonal high water table depth for each map unit was estimated using the Soil Interpretation Records. A Veris® Tech 3100 soil electrical conductivity sensor (Veris Tech. Salina, Kansas) equipped with a differential GPS was used at the beginning of the study to measure soil electrical conductivity (mS m^{-1}) surfaces of the field at 0 to 30 cm (0 to 12 in) (EC_{30}) and 0 to 90 cm (0 to 35 in) (EC_{90}) depths. Site elevation was assessed using a cm-level accuracy Real-Time Kinematic differential GPS device. Digital elevation models and terrain attributes were developed using the appropriate algorithms and commands in Arc/Info® 8.0 (ESRI, Redland, California). Terrain attributes included elevation, slope, profile and plan curvature, flow accumulation, catchment area, and compound topographic index as described by Moore et al. (1993). Map units and terrain attributes were rasterized to a 5 by 5-m (16.4 by 16.4-ft) grid and stacked with surfaces of soil organic C, EC, sand, silt and clay content created by ordinary kriging using GS+® (Gamma Design Software, Plainwell, Michigan). Average soil properties and terrain attributes for each 496 cell was determined using ArcView. The field was subdivided in zones using a fuzzy k-means unsupervised clustering algorithm (Fridgen et al., 2004) using data that was most correlated with crops yield. Optimum numbers of clusters for the field were selected based on the reduction of within-zone crop yield variance (Fraisse et al., 2001).

Statistical analysis. The MIXED procedure in SAS® (SAS Inst., Cary, North Carolina) was used for data analysis (Littell et al., 1996). For the overall field analysis, treatment was considered as fixed effect, while replication and its interactions were considered random effects. For treatment effects within cluster, treatments were considered as fixed effects and sample cells within each cluster as repeated observations. An F statistic with $P \leq 0.05$ was used to determine the significance of the fixed effects for all analyses. Pearson correlation coefficients were calculated between soil properties, terrain attributes and ΔSOC for each treatment. Regression models between ΔSOC and soil properties/terrain attributes and crop C inputs were obtained for each treatment using stepwise regression in SAS® ($P \leq 0.05$) (Freund and Littell, 2000).

Results and Discussion

Rainfall. Soil water regime is known to be one of the major factors affecting crops biomass production and soil organic C dynamics. Rainfall distribution differed greatly during row-crop growing seasons. Precipitation during May to Aug of 2001 and 2002 was 14 percent and 33 percent below the long-term average (430 mm; 17 in), respectively.

On average, the rainfall during the study period was 12 percent lower than the annual

Table 2. Soil management system effects on soil bulk density and soil organic carbon (C) measured at three depths after one corn-cotton rotation cycle (30 months) from a 9-ha experiment in east-central Alabama (2001 to 2003).

		Management system				
		Conventional		Conservation		
Soil depth	Initial	No manure	Dairy manure	No manure	Dairy manure	Standard error
(cm)		(Bulk density, Mg m^{-3})				
0-5	—*	1.35 ab†	1.28 b	1.39 a	1.30 b	0.037
5-15	—	1.57 b	1.52 c	1.62 a	1.62 a	0.011
15-30	—	1.59 ab	1.60 a	1.57 b	1.59 ab	0.011
0-30	—	1.54 a	1.52 b	1.56 a	1.55 a	0.009
		(Soil C, Mg ha^{-1})				
0-5	5.24 c†	5.02 c	7.32 b	7.62 b	12.91 a	0.578
5-15	9.62 b	9.61 b	11.78 a	9.42 b	9.74 b	0.376
15-30	8.84 a	8.77 a	9.90 a	9.08 a	9.93 a	0.565
0-30	23.69 d	23.45 d	29.13 b	26.15 c	32.59 a	0.985

*** Bulk densities not measured at initiation of experiment.**

† Least square means followed by the same letter within a row are not significantly different at $P \leq 0.05$ level.

long term average (1330 mm yr^{-1}; 52.4 in yr^{-1}).

Overall field soil organic carbon. Although there are controversies regarding gravimetric or volumetric bases for expressing soil organic C changes (McCarty et al., 1998), there were only minor treatments effects on soil bulk density in the overall 0 to 30 cm (0 to 12 in) layer in our test (Table 2). On average, the conventional system + manure resulted in slightly lower bulk density in the 0 to 30 cm (0 to 12 in) depth than the other treatments. Treatments that included manure had lower soil bulk density in the 0 to 5 cm (0 to 2 in) depth than treatments without manure. On the other hand, conservation systems had higher soil bulk density in the 5 to 15 cm (2 to 6 in) depth compared with conventional systems, regardless of manure addition.

Initial (2000) soil organic C content in the 0 to 30 cm (0 to 12 in) depth at the site (23.69 Mg ha^{-1} or 10.58 t ac^{-1}) was similar to values commonly reported for Coastal Plain croplands under conventional systems (Motta et al., 2002; Reeves and Delaney, 2002). No significant soil organic C changes in the 0 to 30 cm (0 to 12 in) layer were observed in the conventional system after one rotation cycle (23.45 Mg ha^{-1} or 10.47 t ac^{-1}) compared with the initial soil organic C content at the site (Table 2). However, either conservation system or manure addition imposed for only one rotation cycle significantly increased soil organic C in the 0 to 30 cm (0 to 12 in) depth. On average, the conservation system increased soil organic C by 10 percent compared to initial soil organic C content, but the conservation system coupled with manure had a 38 percent increase in soil organic C.

As would be expected, the major impacts of soil management systems on soil organic C were observed in the 0 to 5 cm (0 to 2 in) depth and were obtained with the combination of manure addition and conservation practices (Table 2). After just one rotation cycle, the conservation system + manure had 157 percent more soil organic C in the 0 to 5 cm (0 to 2 in) layer than conventional system (5.02 Mg ha^{-1}; 2.24 t ac^{-1}), while conservation system without manure and conventional system + manure had 52 percent and 46 percent greater soil organic C compared with the conventional system without manure, respectively. Although no significant differences in soil organic C were found among conventional system without manure and conservation systems with or without manure in the 5 to 15 cm (2 to 6 in) depth, the conventional system with manure resulted in 23 percent more soil organic C (11.78 Mg ha^{-1}; 5.25 t ac^{-1}) than the average of those treatments (9.59 Mg ha^{-1}; 4.28 t ac^{-1}), attributable to manure incorporation by tillage at that depth. Finally, there was a trend for treatments including manure to have more soil organic C in the 15 to 30 cm (6 to 12 in) soil layer than treatments without manure.

Dissimilarities between soil management systems for soil organic C in the 0 to 30 cm (0 to 12 in) depth were related to the amounts of C inputs from crop residues and manure (Table 3), and to soil tillage intensity. Over the entire field, the conservation system with or without manure produced 55 percent greater above ground plant residue over the study period than conventional systems as a result of the inclusion of cover crops and improved row-crop productivity. No manure effects on C inputs from crop residues were observed in either management system, but both the conservation and conventional systems with manure received an extra 8.45 Mg C ha^{-1} (3.77 t ac^{-1}) input, explaining their field-wide soil organic C increases during the study. The conservation system without manure, conventional system with manure, and conservation system with manure treatments received 62 percent, 168 percent and 225 percent higher C inputs than the conventional system without manure (5.23 Mg C ha^{-1}; 2.33 t ac^{-1}), respectively, during the measurement period. The conventional system, the historical management regime for the field, mixed crop residues into the soil surface and promoted a nearly even depth distribution of soil organic C, but manure additions in this management system increased soil organic C content and its stratification. Soil organic C redistribution with depth in the conservation system was due to the change in crop-residue management that minimized crops residues mixing with soil. Accumulation of crop residues on the soil surface in the conservation systems, regardless of manure treatment, more than compensated for mineralization of soil organic C in the 0 to 30 cm (0 to 12 in) depth and resulted in a soil organic C increase over the entire field, even in the initial years of the transition from conventional to conservation practices.

Although the general trends of these results were in agreement with other short term studies (Wood et al., 1991; McCarty et al., 1998), the overall magnitude of changes in soil organic C storage and depth distribution due to soil management systems and manure over such a short time period were a bit unexpected in view of other results (Six et al.,

Table 3. Soil management system effects on plant-residue dry matter and carbon (C) inputs in one corn-cotton rotation cycle (2 years) from a 9-ha experiment in east-central Alabama (2001 to 2003).

	Management system				
	Conventional		Conservation		
	No manure	Dairy manure	No manure	Dairy manure	Standard error
	Residue dry matter (Mg ha^{-1})				
Cover crops-weeds	1.48 b*	1.87 b	7.64 a	7.41 a	0.509
Row-crops	10.84 b	11.20 b	12.02 a	12.29 a	0.319
Manure†	0.00	30.06	0.00	30.06	—
Total biomass input	12.32 d	43.13 b	19.70 c	49.80 a	0.548
	C (Mg ha^{-1})				
Cover crops-weeds	0.47 b	0.66 b	3.26 a	3.17 a	0.224
Row-crops	4.77 b	4.94 ab	5.20 a	5.32 a	0.142
Manure†	0.00	8.45	0.00	8.45	—
Total C input	5.25 d	14.05 b	8.48 c	16.96 a	0.234

*** Least square means followed by the same letter within a row are not significantly different at $P \leq 0.05$ level.**

† Manure input not a response variable.

2002; Causarano et al., 2005). Six et al. (2002), reviewing studies in United States and Brazil, found a general increase in C levels (≈ 0.325 ± 0.113 Mg C ha yr^{-1}; ≈ 0.145 ± 0.05 t ac^{-1}) under no till compared with conventional tillage under temperate and tropical soils. Similarly, Causarano et al. (2005), in an extensive review of soil organic C sequestration potential in cotton production systems of the southeastern United States, reported a 0.310 Mg ha^{-1} yr^{-1} (± 0.350 Mg ha^{-1}; 0.138 ± 0.156 t ac^{-1}) of soil organic C increase after a change from conventional systems to conservation systems in Coastal Plain soils (10.5 year average). However, none of the studies reviewed by Causarano et al. (2005) provided the intensity of C inputs as in the conservation systems of our study. We hypothesize that the C sequestration rate obtained in the conservation system in our study was a result of the warm humid climate (i.e., a long growing season with high potential for photosynthetic fixation of C), the high-residue production from the intensive cropping system, and the low initial soil organic C at the site. Long term experiments in southern Brazil under warm subtropical humid climates combining no-till with intensive cropping rotations showed higher C sequestration rates than those found in United States under colder temperate climates (Bayer et al., 2000; Sa et al., 2001). Carbon sequestration rates of 0.99 and 1.33 Mg C ha yr^{-1} (0.44 and 2.98 t ac^{-1}) reported by Sa et al. (2001) and Bayer et al. (2000) respectively were similar to the rates observed in our trial under similar climatic conditions and cropping intensity. In another review, West and Post (2002) found that change from conventional tillage to no till can sequester 0.57 ± Mg C ha^{-1} yr^{-1} (0.25 t ac^{-1}), but this rate was significantly increased if rotations included corn (e.g., corn-soybean, 0.90 Mg C ha^{-1} yr^{-1}; 0.40 t ac^{-1}) or a change from monoculture. Their results suggested that soil organic C accumulation in response to improved soil management practices is likely to be greatest on soils with a history of intensive cultivation with conventional tillage, because soils that have lost the most C stand to gain the greatest.

We speculate that most of the soil organic C changes measured in our test corresponded to increases in more labile soil organic C fractions, especially particulate organic matter. Particulate organic matter is very sensitive to changes in soil management (Franzluebbers, 1997). We did not measure particulate organic matter during the first 30-month rotation cycle reported here, but plan to do so after another rotation cycle.

Row-crop yield responses. Row-crop yields were affected by soil management system, but were not affected by manure addition (Table 4). Cotton seed yield was 12 percent and 24 percent greater in conservation systems than in conventional systems in 2001 and 2002, respectively. No treatments effects on corn grain yield were observed in 2001, but in 2002, corn yield in conservation systems was 32 percent greater than in conventional systems. The yield increases with the conservation system (regardless of manure treatment) were attributed to improved soil water use efficiency and to the extra nitrogen (N) supply from legumes (data not shown). The lack of yield response to manure additions during the study was in agreement with the general findings that manure impacts on productivity are largely obtained in the long term (Reeves, 1997). A further discussion of treatment impacts on row-crop productivity is beyond the scope of this paper, but the fact that soil organic C increased in conservation systems during the transition from conventional systems concurrently with an increase in crops yields represents strong support for immediate benefits of conservation system adoption by producers on these degraded soils.

Table 4. Soil management system effects on crop yields in one 30-month corn-cotton rotation cycle from a 9-ha experiment in east-central Alabama.

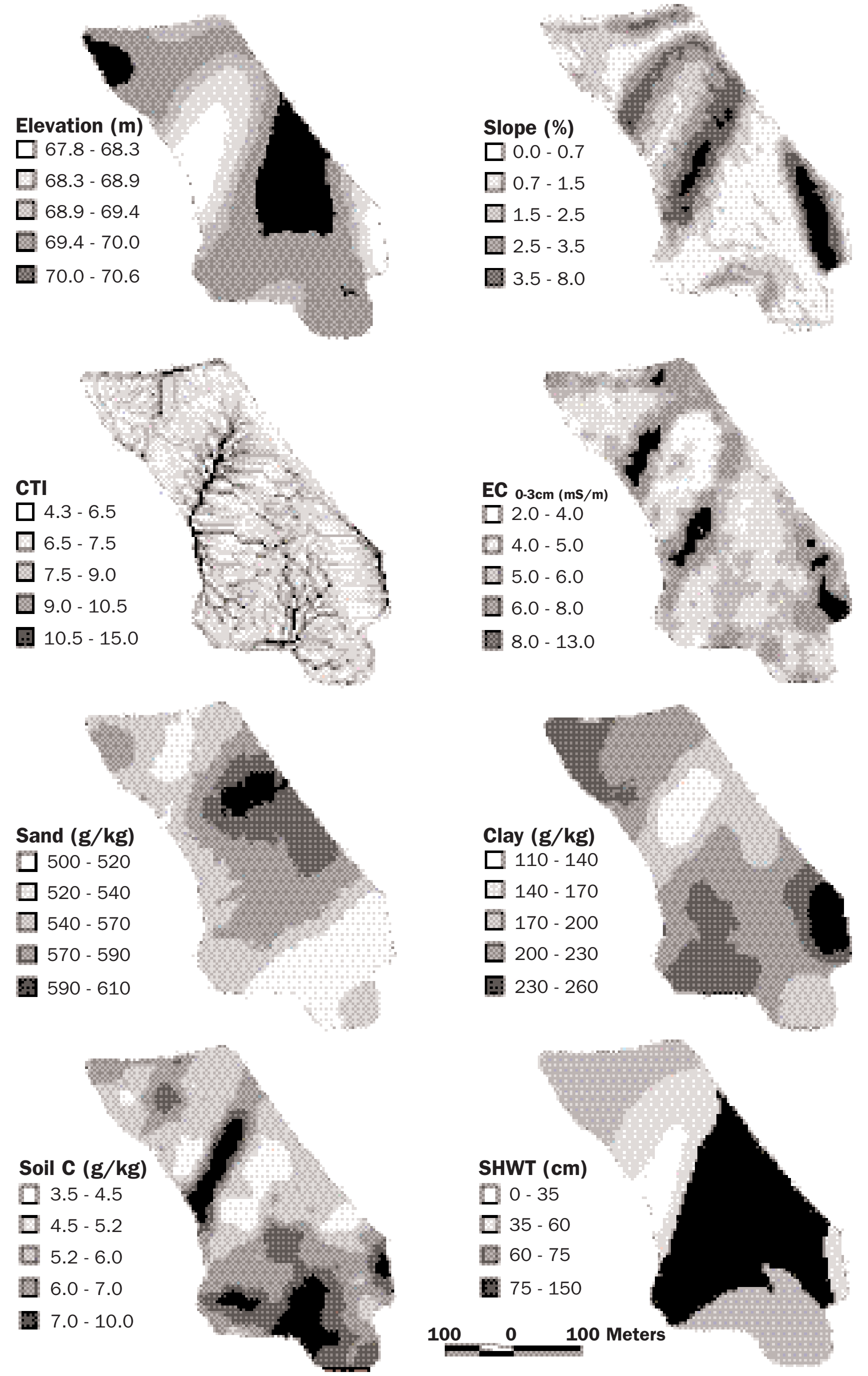
	Cotton seed yield		Corn grain yield	
Treatment	2001	2002	2001	2002
	Mg ha^{-1}			
Conventional system	2.76 b*	1.26 b	9.52 a	6.77 b
Conventional system + manure	2.90 b	1.35 b	9.99 a	6.64 b
Conservation system	3.10 a	1.61 a	9.88 a	8.72 a
Conservation system + manure	3.14 a	1.63 a	10.01 a	9.04 a
Standard error	0.081	0.056	0.250	0.180

*** Least square means followed by the same letter within a column are not significantly different at $P \leq 0.05$ level.**

Soil organic C relationships with C inputs and soil and terrain attributes. Soil properties and terrain attributes indicated substantial landscape variability for the field (Figure 2). Soils mainly vary due to differences in both drainage class and surface horizon textures (mostly due to historical erosion). Soils ranged from well-drained upland Paleudults to somewhat poorly drained soils in concave and relatively lower landscape positions.

Figure 2

Surfaces of elevation, slope, compound topographic index (CTI), soil electrical conductivity (EC), sand content and clay content (0 to 30 cm), soil organic carbon (0 to 30 cm), and seasonal high water table (SHWT) on a 9-ha field in east-central Alabama.



Correlations of initial soil organic C with compound topographic index (CTI) (r = 0.48), electrical conductivity at 90 cm (36 in) (EC$_{90}$) (r = -0.42), silt content (r = 0.39) and slope (r = -0.41) suggests that historical erosion and field-scale water dynamics played a major role on soil carbon variability across the field.

Correlation coefficients between soil and terrain attributes and C residue inputs with change in soil organic C ΔSOC after one rotation cycle for each management system are presented in Table 5. Analysis by treatment revealed that neither terrain attributes nor soil seasonal high water table correlations with ΔSOC were significant in any system. Sand content was positively correlated with ΔSOC but only in conservation systems. Clay content was negatively correlated with ΔSOC only in no-till. Although initial soil organic C was relatively low across the field on average (23.69 Mg ha^{-1}; 10.58 t ac^{-1}), it was an important soil attribute for explaining ΔSOC within treatments in the field. The negative correlation between initial soil organic C and ΔSOC for all treatments indicated that C sequestration rates were highest on landscape positions that originally had the lowest soil organic C content. Carbon input from crop residues was correlated with ΔSOC only in treatments that did not include manure. In conservation systems, there was a positive correlation between C crop residue inputs and ΔSOC, but the opposite trend was observed for conventional systems. Regression models relating soil properties and terrain attributes with ΔSOC explained between seven percent (conventional system + manure) to 47 percent (conservation system + manure) of the variability depending on treatment (Table 5). Initial soil organic C content across the landscape was the most significant parameter in the regression models for all treatments, but its relative contribution was highly variable among treatments. Soil electrical conductivity for 30-cm (12 in) depth (EC$_{30}$) was a significant parameter in the regression models of the conservation systems and was negatively related with ΔSOC.

The lack of a clear pattern between soil and terrain attributes and ΔSOC for treatments during this three-year study may be evidence that the management systems had not reached equilibrium. According to Rhoton (2000), adoption of no till practices on cotton resulted in substantial improvements of soil quality within four years of adoption, but significant enhancement was observed up to eight years after adoption.

Soil organic C responses to soil management systems within clusters. Given that the maximum yield variance reduction was achieved with five clusters (data not shown), we chose those clusters to compare treatment effects on soil organic C after one rotation cycle (Figure 3). Averages of soil properties and terrain attributes for each of the five management zone clusters delineated are presented in Table 6. There were significant

Table 5. Correlation coefficients (r) and coefficients of determination (R^2) from stepwise regression relating change in soil organic carbon (ΔSOC) after one rotation cycle with soil properties (0 to 30 cm depth), terrain attributes and C inputs for each treatment on a 9-ha experiment in east-central Alabama ($P \leq 0.05$; n ≈ 60 per treatment).

	Management system			
	Conventional		Conservation	
	No manure	Dairy manure	No manure	Dairy manure
Elevation	NS*	NS	NS	NS
Slope	NS	NS	NS	NS
Catchment area	NS	NS	NS	NS
Compound topographic index	NS	NS	NS	NS
Electrical conductivity$_{(0\text{-}30\ cm\ depth)}$	NS	NS	-0.35†	NS†
Electrical conductivity$_{(0\text{-}30\ cm\ depth)}$	0.26	NS	NS	NS
Sand$_{(0\text{-}30\ cm\ depth)}$	NS	NS	0.36	0.39
Silt$_{(0\text{-}30\ cm\ depth)}$	NS†	NS	NS	NS
Clay$_{(0\text{-}30\ cm\ depth)}$	NS	NS	-0.36	NS
Water table depth	NS	NS	NS	NS
Initial soil organic C$_{(0\text{-}30\ cm\ depth)}$	-0.53†	-0.26†	-0.32†	-0.63†
C crop residue inputs	-0.25	NS	0.40†	NS
R^2	0.36	0.07	0.38	0.47

*** NS = correlation not significant at $P \leq 0.05$ level.**

† Variable retained in the stepwise regression model.

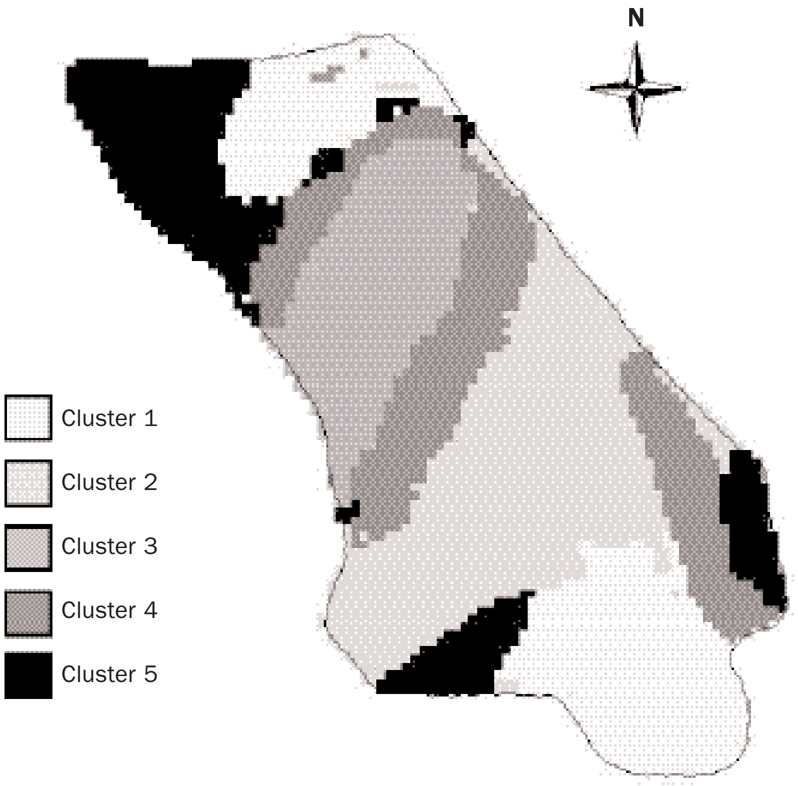


Figure 3

Fuzzy k-means classification of a 9-ha field in east-central Alabama into five management zones using the following soil properties (0 to 30 cm) and terrain attributes: elevation, slope, compound topographic index, electrical conductivity (0 to 30 cm and 0 to 90 cm), sand content, clay content, soil organic carbon and seasonal high water table depth.

treatment effects on ΔSOC (0 to 30 cm depth; 0 to 12 in) in all clusters (Table 7). In general, manure addition had the greatest impact on soil organic C increases in all clusters, regardless of soil management system. The greatest ΔSOC difference between conservation systems and conventional systems were obtained in clusters 1, 2, and 3; clusters of higher C biomass input and row-crop productivity (data not shown). For discussion purposes we will concentrate only on the three clusters that better typify the landscape variability (2, 3, and 4).

Cluster 2 was an elevated area of relatively flat topography dominated by well-drained soils with sandy surfaces and a deep seasonal high water table. The conservation system with manure had consistently greater ΔSOC than the other treatments in this upland landscape. Manure addition increased soil organic C in conventional tillage+M compared to initial soil organic C conditions, but the increase was not different than the soil organic C increase obtained with the conservation system without manure in this cluster. Cluster 3 corresponded to a concave drainage way position occupying the lowest elevation in the field, with more poorly drained soils that accumulated eroded sediments from upslope areas. Manure addition increased ΔSOC in both management systems but no ΔSOC differences were observed between soil management systems at the same level of manure treatment. The highest positive ΔSOCs for the conventional system without manure, conventional system with manure, and conservation system without manure were observed in this landscape position. Cluster 4 corresponded to areas situated on sloping eroded soils with high EC and clay content, and low soil organic C and compound topographic index. The conservation system coupled with manure had the greatest impacts on ΔSOC in this cluster and dominated ΔSOC for the entire field overall. The greatest differences in ΔSOC between the conservation system with manure and other treatments were also obtained in cluster 4. Wood et al. (1991), in semi-arid Colorado, reported that the greatest soil organic C increases in the 0 to 10 cm (0 to 4 in) depth after four years adoption of a no-till intensive cropping system occurred in the footslope and summit positions and the lowest in the backslope position.

Table 6. Averages of soil properties (0 to 30 cm) and terrain attributes for five clusters developed by k-means clustering in a 9-ha experiment in east-central Alabama.

Variables*	Elevation	Slope	CTI	EC_{30}	EC_{90}	SHWT	Sand	Clay	SOC
	(m)	(%)		—— mS m^{-1} ——		(cm)	—— g kg^{-1} ——		(Mg ha^{-1})
Cluster 1	69.8	1.0	7.5	5.5	6.7	79	519	182	26.40
Cluster 2	70.1	0.8	7.5	5.0	6.3	150	556	191	23.85
Cluster 3	68.5	1.7	8.1	4.6	6.0	61	573	143	24.01
Cluster 4	69.4	3.3	6.8	7.2	7.6	132	552	193	20.38
Cluster 5	69.6	1.3	7.4	5.6	5.9	73	533	211	24.08

*** CTI = Compound topographic index.**

EC_{30} = Soil electrical conductivity 0 to 30 cm.

EC_{90} = Soil electrical conductivity 0 to 90 cm.

SHWT = Seasonal high water table depth.

SOC = Initial soil organic carbon 0 to 30 cm.

Table 7. Effect of soil management system and manure addition on change in soil organic carbon (ΔSOC) (0 to 30 cm depth) in one corn-cotton rotation cycle on five clusters of a 9-ha experiment in east-central Alabama (2001 to 2003).

	Management system				
	Conventional		Conservation		
Cluster	No manure	Dairy manure	No manure	Dairy manure	Standard error
	——— ΔC Mg ha^{-1} ———				
Cluster 1	-0.52 c*	6.25 a	2.61 b	7.74 a	1.452
Cluster 2	-0.81 c	3.35 b	2.49 b	8.67 a	1.290
Cluster 3	1.24 b	7.87 ab	4.05 b	8.22 a	2.060
Cluster 4	0.26 c	4.43 b	1.25 c	10.01 a	1.398
Cluster 5	-1.99 b	4.91 a	0.20 b	6.35 a	2.268

*** Least square means followed by the same letter within a row are not significantly different at *P* ≤ 0.05 level.**

Summary and Conclusion

No-till cropping coupled with intensive production of residue from cover crops on degraded coastal plain soils previously managed under row crop monoculture and conventional tillage for several decades increased soil organic C storage (10 percent) and altered soil organic C distribution in the 0 to 30 cm (0 to 12 in) depth in only thirty months. The highest impacts on ΔSOC (+38 percent) compared to field soil organic C initial condition were observed from the joint effect of a high-residue intensive conservation system coupled with manure amendments. In our trial, conservation systems not only increased soil organic C but also averaged 14 percent and 15 percent greater corn and cotton yields, respectively, than conventional systems, averaged over the entire field, regardless of manure addition.

Carbon input from crop residues was an important variable explaining ΔSOC across the landscape only in conservation systems. Initial soil organic C content was the most common correlated variable with ΔSOC across the landscape for all treatments during the study. This suggests that conservation systems may have greater soil organic C increases relative to conventional systems at low soil quality landscape positions. The highest soil organic C increase with respect to initial field soil organic C was observed in the concave drainage way position (Cluster 3) for conventional systems, regardless of manure additions, and the conservation system without manure, and in eroded slopes (Cluster 4) for the conservation system with manure.

Our results suggest that for degraded soils in warm humid climates, like those prevalent in the Coastal Plain of the Southeast, a high-residue producing cropping system using cover crops and no tillage can increase row crop productivity, sequester C, and improve soil quality even during the initial years of adoption.

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