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Potential for Soil Carbon Sequestration in Cotton Production Systems of the Southeastern USA

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Abstract

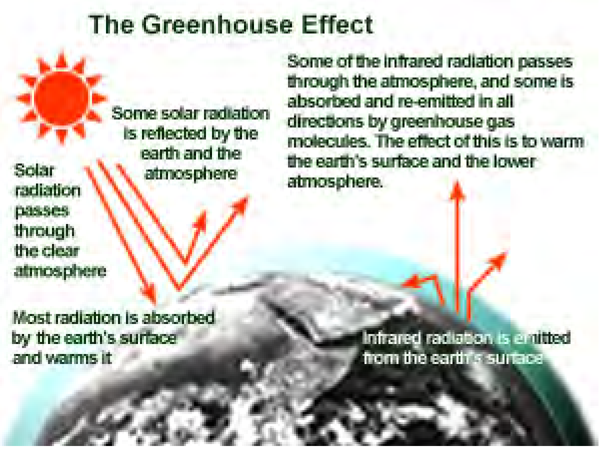
Past agricultural management practices have contributed to the loss of soil organic carbon (C) and emission of greenhouse gases [e.g., carbon dioxide (CO_2) and nitrous oxide (N_2O)]. Fortunately however, conservation-oriented agricultural management systems can be, and have been, developed to sequester soil organic C, improve soil quality, and increase crop productivity. Soil organic C sequestration is intimately associated with agronomic productivity, environmental quality, and economic opportunities and returns.

The objectives of this project were to:
- Review published and unpublished scientific literature related to soil organic C sequestration in cotton production systems
- Recommend best management practices to sequester soil organic C in cotton production systems of the southeastern USA
- Outline current political scenario and future probabilities for cotton producers to benefit from soil organic C sequestration

From a review of 20 studies in the region, soil organic C increased with no tillage compared with conventional tillage by an average of 430 lb C acre^{-1} year^{-1}. Variation in this estimate was large, but this was expected based on the diversity of soils, cropping systems, and experimental conditions that occurred among locations. By implementing no tillage continuously for 10 years on a typical soil in the southeastern USA, soil organic C to a depth of 8” could be expected to increase from 11.2 ton acre^{-1} initially to 13.4 ton acre^{-1} (19% increase). More diverse rotations of cotton with high-residue-producing crops such as corn and small grains would sequester greater quantities of soil organic C than continuous cotton. Available data suggested that no-tillage cropping with a cover crop sequestered 600 lb C acre^{-1} year^{-1}, while that of no-tillage cropping without a cover crop sequestered 300 lb C acre^{-1} year^{-1}. Conservation tillage, cropping system intensification, sod-based crop rotations, and judicious use of fertilizers and herbicides were some of the agricultural practices shown to be successful in increasing soil organic C. Current government incentive programs recommend agricultural practices that would contribute to soil organic C sequestration. Participation in the Conservation Security Program could lead to government payments of up to $8 acre^{-1}. Current open-market trading of C credits would appear to yield less than $1 acre^{-1}, although prices would greatly increase should a government policy to limit greenhouse gas emissions be mandated.

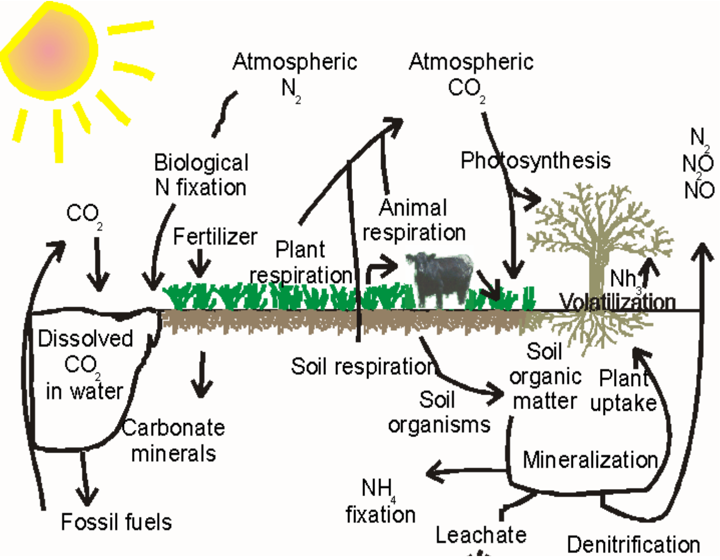
1. CO_2 and Climate Change

The concentration of carbon dioxide (CO_2) in the atmosphere has increased from 280 ppmv (part per million by volume) during pre-industrial times to about 375 ppmv in 2002 at Mauna Loa Observatory, Hawaii, with most of the increase during the past 50 years a result of fossil-fuel burning (IPCC, 2001). All indications suggest that atmospheric CO_2 concentration will continue to increase, raising concern by the scientific community about the potential detrimental effects of rising CO_2 and other greenhouse gases [methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and chlorofluorocarbons (CFCs)] on global warming and climate change (www.carboncyclescience.gov).



Graphic courtesy of US–Environmental Protection Agency.

Greatest mitigation of rising CO_2 concentration would be attained with reduction in the burning of fossil fuels, but the political and economical costs of such a major change are considered too drastic at this time. An alternative strategy to reduce greenhouse gas emission and allow sufficient time for industries to develop and implement non-fossil-fuel-derived energy utilization strategies relies on understanding and manipulating to the greatest extent possible the natural processes of the global C cycle. Photosynthesis and respiration are the two largest fluxes on a global scale that have kept atmospheric CO_2 in balance in the past (www.esig.ucar.edu/nacp). Either increasing photosynthesis (uptake of CO_2 from the atmosphere by plants) or decreasing respiration (release of CO_2 from plants and soil microorganisms to the atmosphere) would result in less CO_2 being returned to the atmosphere. This mitigation strategy relies on (a) maximizing CO_2 uptake from the atmosphere primarily through reforestation and afforestation, which would sequester C in woody plants and/or (b) minimizing CO_2 release to the atmosphere primarily by sequestering C in soil organic matter through conservation management systems that minimize soil disturbance (www.usda.gov/oce/gcpo). Landowners and agricultural producers that contribute to this mitigation would provide an environmental service to society, and therefore could be monetarily compensated through government programs or through an open-market trading system involving emitters and sequesters of CO_2 and other greenhouse gases.



Generalized diagram of carbon and nitrogen cycles.

Detailed descriptions of the global C cycle and how land use and management would affect pools and fluxes of C are available in several textbooks (Stevenson, 1986; Schlesinger, 1991; Lal et al., 1998; Follett et al., 2001).

2. Objectives

The objectives of this project were to:

- Review published and unpublished scientific literature related to soil organic C sequestration in cotton (*Gossypium hirsutum* L.) production systems of the southeastern USA (Fig. 1).
- Recommend best management practices to sequester soil organic C in cotton production systems for specific major land resource areas in the region.
- Outline current political scenario and future probabilities for cotton producers to benefit from soil organic C sequestration.

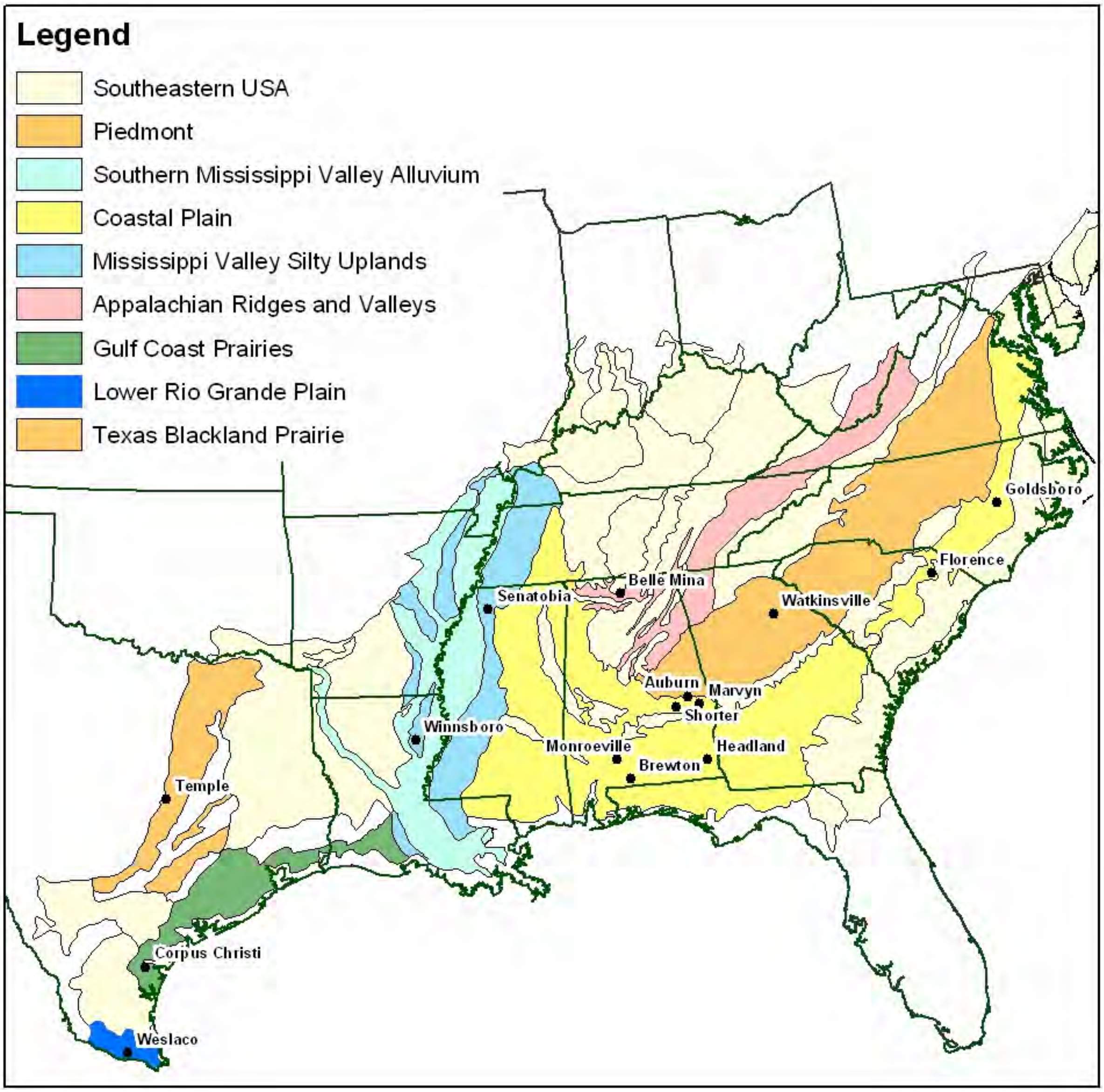


Figure 1. The southeastern USA with delineation of major land resource areas and locations where research on soil organic C with conservation tillage in cotton production systems has been determined.

3. Agricultural Role in Soil Organic C Sequestration

Agriculture and forestry in the USA directly emit 8% of the total greenhouse gas emission of the nation (USDA, 2004). This estimate does not account for a potentially large sink in wood and soil organic matter. Although agricultural emission is a relatively small portion of the total, the potential sinks suggest that agriculture and forestry could act as key components to reduce the nation's burden of greenhouse gas emission.

Agricultural activities could mitigate greenhouse gas emission by: (1) direct emission reduction, e.g., lower fossil-fuel consumption with fewer field passes using conservation tillage, (2) sequestering C in plant biomass and soil organic matter, (3) producing biofuels that would substitute for fossil fuels, and (4) reducing commercial application of high-energy-input N fertilizer by relying on biologically fixed N, increasing nutrient cycling efficiency, and relying on technologies to make informed decisions of how much N is required for optimum yield. Soil organic matter contains the largest global terrestrial C pool (Schlesinger, 1991). Crop management practices to increase this C pool in soil might include reduction in tillage intensity, reduction or elimination of fallow periods, intensifying cropping with the use of crop rotations and cover crops, and judicious use of inputs (e.g., pesticides, irrigation, fertilizers and manures) to increase primary production and produce more crop residue (Paustian et al., 1997; Lal et al., 1998; Follett, 2001). Grass management systems may have even greater potential to sequester C in soil due to vigorous rooting, lack of soil disturbance, and diversity of perennial species (Follett et al., 2001). Sod-based crop rotations with conservation tillage could be an innovative use of an historical conservation technology for increasing C sequestration in cropland soils (Studdert et al., 1997; Diaz-Zorita et al., 2002; Garcia-Prechac et al., 2004).

3.1. The Southeastern USA

For the purposes of this paper, we define the southeastern USA to include eastern Texas, southeastern Arkansas, Louisiana, Mississippi, Tennessee, Alabama, Georgia, Florida, South Carolina, North Carolina, and Virginia (Fig. 1). Mean annual temperature ranges from 57 °F (14 °C) in the northern sections to 77 °F (25 °C) in the southern sections. Mean annual precipitation typically exceeds 39" (1000 mm) throughout the region, but is highest along the coastlines and in the central section (>55", 1400 mm). Figure 2 shows the range of climatic conditions that occur geographically and seasonally in the region.

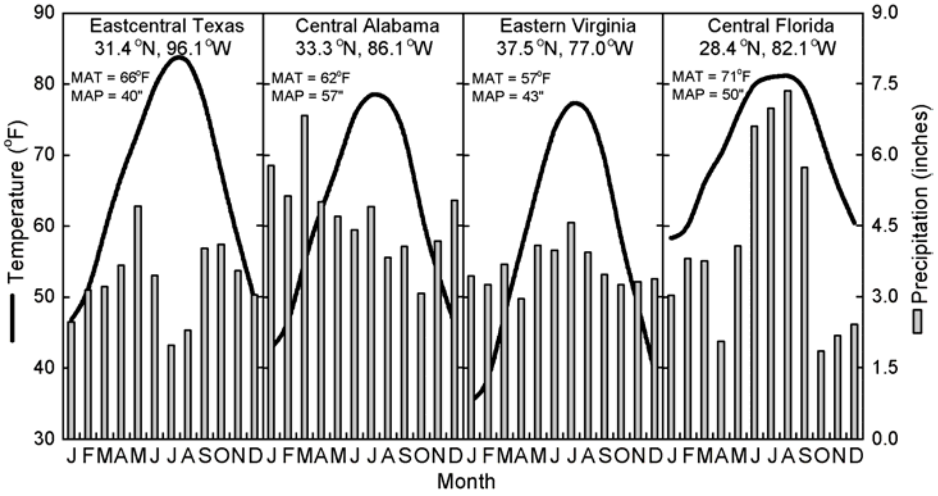


Figure 2. Mean annual temperature and precipitation at four locations within the southeastern USA. Data from the National Climatic Data Center (http://www.ncdc.noaa.gov/oa/ncdc.html).

Although soils in the southeastern USA typically have relatively low organic

C compared with other parts of North America (Jenny, 1930), the potential for significant soil organic C sequestration in the region may be higher. Reasons for this viewpoint follow. With sound soil and crop management, the warm and humid climate with a long growing season allow for high cropping intensity and biomass production; which translates into high potential for photosynthetic C fixation (Reeves and Delaney, 2002). The long history of exhaustive tillage and subsequent soil erosion has depleted soil organic C in the region. Through conservation efforts during the past century, organic C in many soils has rebounded with the implementation of conservation tillage, pasture-based animal agriculture, and the planting of trees. Stabilization of soil by avoiding soil disturbance and producing high plant biomass are the primary drivers for creating a positive balance that determines the formation of soil organic C (Fig. 3). The diversity of land use and the potential for flexible land-use rotation due to favorable climatic conditions offer agricultural producers in the southeastern USA more opportunities to maximize soil C sequestration than in other regions.

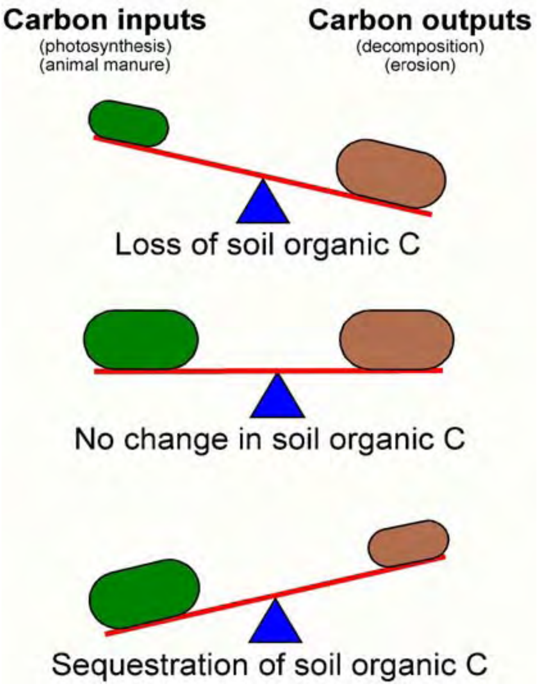
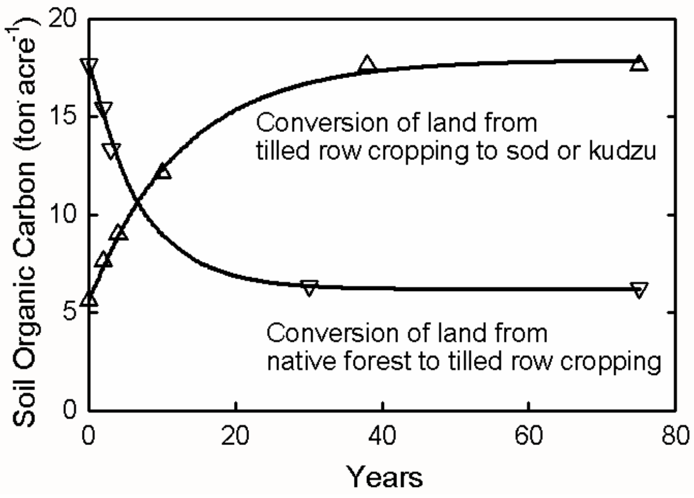


Figure 3. Representation of how the balance between C inputs and outputs affect soil organic C. Factors affecting C inputs are related to productivity of plants and addition of C in manure and byproducts. Factors affecting C outputs are soil disturbance, erosion, and availability of water.

Surface residue management is especially critical in the southeastern USA, because soils are highly erodible and high-energy rainstorms occur during the growing season (Blevins et al., 1994). Soils of the region have low soil organic C, partly because of the prevailing climatic conditions and soil mineralogy (Jenny, 1930), but also due to historical mismanagement that exposed the soil surface to rapid biological oxidation and extreme soil erosion (Trimble, 1974; Harden et al., 1999). Incorporation of the organic-rich surface soil with tillage following clearing of native vegetation results in a rapid decline in soil organic C with time (Fig. 4). Fortunately however, conservation management that limits soil disturbance can restore soil organic C (Fig. 4), mainly near the surface since soil organic C is typically very low below 1-foot depth in most soils of the region, irrespective of management (Fig. 5).

Figure 4. Chronosequence of aggrading and degrading management in relation to soil organic C in the plow layer (0-6") of Southern Piedmont soils. Modified from Hendrix et al. (1998) with data from Giddens (1957) and Jones et al. (1966). Degrading management with intensive tillage under cropping causes a rapid decline in soil organic C. Conservation management with continuous cover and no soil disturbance can sequester soil organic C.



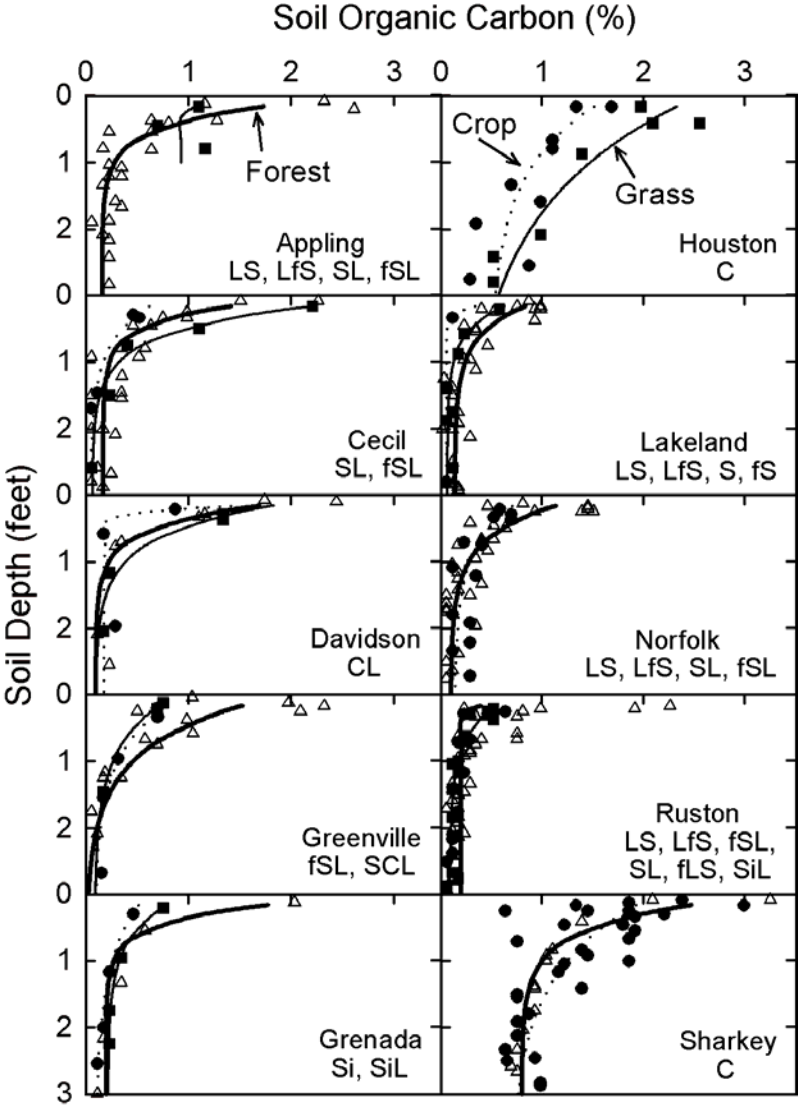


Figure 5. Soil organic C depth distribution from multiple locations within typical soils of the southeastern USA as affected by (i) conventional-tillage cropping, (ii) unmanaged grass, and (iii) forest land use. Soil organic C accumulates near the soil surface under conservation management, but is low and relatively little affected by management below 1-ft depth (<<0.5 % in most coarse-textured soils, 1% in fine-textured soils).

1. **Cropping (● with dotted lines)**
2. **Grassland (■ with thin solid line)**
3. **Forest (Δ with thick solid line.**

Soil textures are clay (C), clay loam (CL), fine loamy sand (fLS), fine sandy loam (fSL), loamy fine sand (LfS), loamy sand (LS), sand (S), sandy clay loam (SCL), sandy loam (SL), silt (Si), and silt loam (SiL). From Franzluebbers (2005) with data from McCracken (1959).

Cotton is one of the most important crops in Alabama, Georgia, Mississippi, and eastern Texas (Table 1). Cotton production has high potential profitability, but historically has been detrimental regarding sustainability of natural resources for the region (Reeves, 1994). From 1860 to 1920, when a majority of the land in the Southern Piedmont region was under cotton cultivation with clean tillage, soil erosion was at its greatest, averaging cumulative loss of 5 to 10” (14 to 24 cm) of soil throughout the region (Trimble, 1974). Although the extent of land cultivated with cotton is now much less than a century ago, the adoption of conservation tillage technology could be a key driver towards increasing land cultivated with cotton. Currently, about 34% of the land cultivated with cotton in the region is being managed with conservation tillage (Table 1). Some large differences in cropping and tillage practices are evident among the 11 states in the region. Reasons for differences among states could be due to (1) adoption greatest in areas with historically severe erosion problems, (2) producers on more fertile bottomland soils have not seen the need for change, and (3) varying leadership and promotion by extension agencies. These data suggest great potential for further adoption of conservation management technologies that could both sequester soil organic C and increase productivity.

Table 1. Land planted to cotton and form of tillage system used in the southeastern USA during 2004 (Adapted from Conservation Technology Information Center, 2004).

State	Land in Cotton		Tillage System of Land in Cotton (%)					
			Conservation Tillage				Reduced Tillage	Conventional Tillage
	Total (million acres)	Percent of Total Cropland	No-till	Ridge-till	Mulch-till	Total		
Alabama	0.54	33	51	4	2	58	16	26
Arkansas	0.86	13	8	9	8	25	21	54
Florida	0.10	7	29	8	26	63	3	34
Georgia	1.31	39	40	0	1	41	12	47
Louisiana	0.47	15	10	16	3	29	40	31
Mississippi	1.09	28	24	1	1	26	21	53
North Carolina	0.74	17	41	2	0	43	17	40
South Carolina	0.22	15	46	1	0	47	8	45
Tennessee	0.52	17	46	0	0	47	8	45
Texas (eastern)	1.02	22	1	0	2	3	19	78
Virginia	0.20	5	71	0	4	75	7	18
Southeastern USA	7.07	24	28	3	2	34	17	49

Situations that accelerate loss of soil C.

Conditions that promote soil C accumulation.

4. Management Strategies to Sequester Soil Organic C

4.1. Conservation tillage

Conventional tillage buries residues, disrupts macroaggregates, increases aeration, and stimulates microbial breakdown of soil organic matter (Reeves, 1997). In contrast, when crop residues and cover-crop mulch are left on the surface (i.e., conservation tillage), they protect the soil against erosion, increase water infiltration, decrease soil water evaporation, and increase soil organic C near the surface. Plant residues decompose slower on the soil surface than when incorporated into soil. Conservation tillage is defined as any system that provides >30% residue cover on the surface after planting. This practice, coupled with efficient management of inputs, can lead to sequestration of soil organic C, while at the same time increasing cotton lint and seed yield (Fig. 6). Yield benefits of conservation tillage have not always been observed, especially in 1- to 2-year studies. The benefit of conservation tillage will often be expressed most significantly in long-term evaluations.

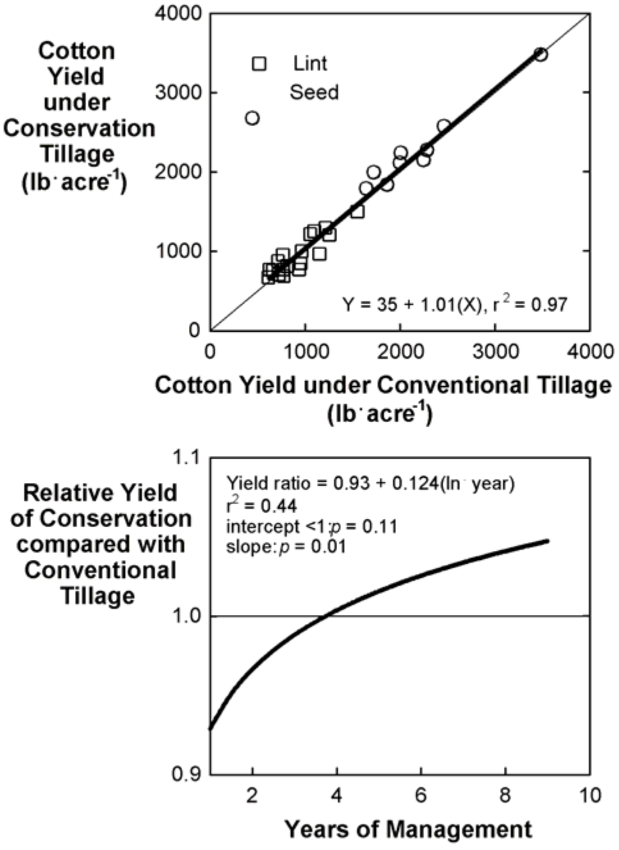


Figure 6. Cotton yield under conservation tillage compared with conventional tillage (top panel) and relative yield under conservation compared with conventional tillage as affected by years of continuous management (bottom panel). Top panel suggests that conservation tillage will either slightly increase yield or keep yield similar to that under conventional tillage. Bottom panel suggests that a transition period exists during the implementation of conservation tillage, where yield may be initially depressed due to nutrient or physical limitations, but that yield will be improved with long-term implementation due to surface organic matter accumulation that affects nutrient cycling and water conservation. Data from Baker (1987), Bauer and Busscher (1993), Boquet and Coco (1993), Buntin et al. (2002), Burmester et al. (1993, 2002), Busscher and Bauer (2003), Dabney et al. (1993), Delaney et al. (2002), Denton and Tyler (2002), Endale et al. (2002), Gordon et al. (1990), Hutchinson et al. (1993), Johnson et al. (2001), Lee et al. (2002), Mitchell et al. (2002), Mutchler et al. (1985), Nyakatawa and Reddy (2002), Nyakatawa et al. (2000), Parsch et al. (2001), Pettigrew and Jones (2001), Reeves and Delaney (2002), Schomberg et al. (2003), Schwab et al. (2002), Triplett et al. (1996, 2002), and Wiatrak et al. (2002).

Average soil organic C sequestration with adoption of conservation tillage was 430 lb acre^{-1} yr^{-1} (0.48 Mg C ha^{-1} yr^{-1}) (Table 2). This rate of soil organic C sequestration for the southeastern USA is nearly identical to an assumed value of 450 lb acre^{-1} yr^{-1} (0.5 Mg C ha^{-1} yr^{-1}) used by Lal et al. (1998) for the entire USA. From 96 observations of all cropping systems in the southeastern USA, Franzluebbers (2005) reported soil organic C sequestration of 375 lb acre^{-1} yr^{-1} (0.42 $\pm$ 0.46 Mg C ha^{-1} yr^{-1}). West and Post (2002) calculated average soil organic C sequestration of 430 lb acre^{-1} yr^{-1} (0.48 ± 0.13 Mg C ha^{-1} yr^{-1}) for no tillage compared with conventional tillage from 93 observations around the world. All of these estimates were similar in magnitude, although they suggest a great deal of variation among individual sites within these reviews. Recent soil organic C sequestration estimates from conservation-tillage management systems in other regions of the world include: 430 lb acre^{-1} yr^{-1} (0.48 ± 0.59 Mg C ha^{-1} yr^{-1}) in the central USA (Johnson et al., 2005), 270 lb acre^{-1} yr^{-1} (0.30 ± 0.21 Mg C ha^{-1} yr^{-1}) in the southwestern USA (Martens et al., 2005), 240 lb acre^{-1} yr^{-1} (0.27 ± 0.19 Mg C ha^{-1} yr^{-1}) in the northwestern USA and western Canada (Liebig et al., 2005), 225 lb acre^{-1} yr^{-1} (0.25 ± 0.45 Mg C ha^{-1} yr^{-1}) in Brazil (Zinn et al., 2005), and 45 lb acre^{-1} yr^{-1} (0.05 ± 0.16 Mg C ha^{-1} yr^{-1}) in Canada (VandenBygaart et al., 2003). From an earlier analysis that did not include many of the observations now available, Franzluebbers and Steiner (2002) outlined a geographical area in North America with the highest soil organic C sequestration potential with adoption of conservation tillage that included the central and upper southeastern USA regions. Clearly, adoption of conservation tillage in the southeastern USA has potential for some of the highest rates of soil organic C sequestration in North America and other parts of the world. Greater adoption of this technology will be advantageous to producers and society in reaping the multiple benefits of C storage in soil.

Table 2. Estimate of soil organic C sequestration with adoption of conservation tillage in different Major Land Resource Areas (MLRA) in the southeastern USA.

MLRA	Number of observations	Depth (inches)	Duration (years)	Soil organic C sequestration (lb acre^{-1} yr^{-1})	
				Mean	Std Dev
Appalachian Ridge and Valley	4	9	7.3	696	571
Coastal Plain	17	8	10.5	277	313
Gulf Coast Prairie	4	8	15.0	170	89
Lower Rio Grande Plain	1	8	8.0	313	–
Mississippi Valley Silty Upland	6	6	8.8	125	143
Southern Piedmont	8	7	6.3	1000	696
Texas Blackland Prairie	1	12	10.0	348	–
Southeastern USA	41	7.5	9.5	430	500

Data in Table 2 were derived from the following sources: Boquet et al. (1997), Ding et al. (2002), Feng et al. (2002), Fesha et al. (2002), Franzluebbers (2002), Franzluebbers et al. (1999), Hunt et al. (1996), Karlen et al. (1989), Motta et al. (2002), Naderman et al. (2004), Novak et al. (1996), Nyakatawa et al. (2001), Potter and Chichester (1993), Potter et al. (1998), Reeves and Delaney (2002), Rhoton (2002), Rhoton et al. (2002), Salinas-Garcia et al. (1997), Siri-Prieto (unpublished data), Siri-Prieto et al. (2002), Terra (unpublished data), Torbert et al. (2004), and Zibilske et al. (2002).

Although these data on soil organic C sequestration in cotton production systems in the southeastern USA represent a great deal of research effort, they also point to a deficiency in obtaining an unequivocal estimate of potential soil organic C sequestration for the entire region, or even on specific soil types within a flexible crop rotation system. More research is needed to better characterize potential soil organic C sequestration, especially with regard to the diversity of soil types, crop rotation sequences, fertility management, and cover crop management. We suggest that a more concerted effort be made to characterize soil organic C sequestration under a wider range of soil conditions in crop rotations that reflect high economic return, stewardship of land, and that minimize the impact on the environment.

4.2. Crop Rotation and Cover Cropping

Perhaps more than any other crop, good residue management is critical in cotton, because of its sparse residue production. Good residue management can be achieved with a sound crop rotation and use of cover crops in combination with conservation tillage. Unfortunately, high profitability of cotton often leads to cotton monoculture (Reeves, 1994). Scientific literature addressing the impact of crop rotation on soil organic C under cotton production in the southeastern USA is rather scarce. The 'Old Rotation' experiment at Auburn University was initiated in 1896 to determine (1) the effect of rotating cotton with other crops to improve yields and (2) the effect of winter legumes in cotton production systems (Mitchell and Entry, 1998). Seed cotton yield during a 10-year period from 1986-1995 was greater in rotation with corn (*Zea mays* L.) and winter legumes than under monoculture cropping. Mitchell and Entry (1998) demonstrated a positive association of soil organic C with cotton seed yield, suggesting that higher biomass inputs from cover crops and corn in rotation with cotton improved soil organic C sequestration and cotton productivity. With 98 years of cultivation, 2- and 3-year rotations of cotton with corn and soybean [*Glycine max* (L.) Merr.] resulted in soil organic C concentration of 1% (10 g kg^{-1}), while soil organic C under continuous cotton with legume cover crop was 0.75% (7.5 g kg^{-1}) and under continuous cotton without cover crop was 0.39% (3.9 g kg^{-1}) (Reeves, 1997). With the introduction of conservation tillage to the experiment in 1995, the benefits of crop rotations and cover crops to cotton productivity and soil organic C concentration have been enhanced (Mitchell et al., 2002; Siri-Prieto et al., 2002).

Cover crops grow during periods when the soil might otherwise be fallow and exposed to decomposition and heavy rains. Cover crops (1) protect the soil from water runoff, wind and water erosion, and nutrient leaching, (2) suppress weeds, (3) control pests, and (4) promote sequestration of soil organic C. Available data from the scientific literature suggests that soil organic C sequestration with adoption of conservation tillage compared with conventional tillage without a cover crop (n = 23) was 300 lb acre^{-1} yr^{-1} (0.34 ± 0.47 Mg C ha^{-1} yr^{-1}), while the rate of sequestration with a cover crop (n = 18) was 600 lb acre^{-1} yr^{-1} (0.67 ± 0.63 Mg C ha^{-1} yr^{-1}). These data indicate that including a cover crop in a conservation tillage system can essentially double the C sequestration benefit from that expected using conservation tillage alone.


Balansa clover


Crimson clover


Sunn hemp

Reeves and Delaney (2002) compared monoculture cotton with an intensive cropping system that maintained actively growing cash or cover crops about 330 days of the year using sunn hemp (*Crotolaria juncea* L.) and ultra-narrow row cotton (UNR; 8” row spacing) in a rotation with wheat (*Triticum aestivum* L.) and corn. All UNR systems exhibited higher net returns than traditional row spacing with highest net return over variable costs obtained using continuous no-tillage UNR cotton (\$104.57 acre^{-1} yr^{-1}), which was a function of higher cotton yield and commodity support programs for cotton. The no-tillage, intensive-cropping system had the second highest net return (\$97.20 acre^{-1} yr^{-1}). Although short-term economics are important to producers, maintenance or improvements in soil organic C will increase productivity and sustainability in the long-term.

When practiced in monoculture or even in double cropping, no tillage is an imperfect and incomplete system according to Rolf Derpsch (www.rolf-derpsch.com), in which diseases, weeds and pests tend to increase and profits tend to decline with time. The adoption of conservation tillage along with cover cropping as a “conservation system approach”, as promoted by this research and extension specialist in South America, has led to rapid adoption of conservation tillage in many South American countries. Paraguay is now the leading country in the world in terms of percentage of cropland managed with no tillage at 60%.

4.3. Fertilizers and Manures

Fertilizer or manure application would be expected to increase soil organic C, because of greater C input associated with enhanced primary production and crop residues returned to the soil. Only limited data are available in the southeastern USA to assess long-term fertilization effects on soil organic C sequestration. Using available data from six literature sources of various crops in the region, Franzluebbers (2005) estimated that the net C offset due to N fertilization could be optimized at 215 lb acre^{-1} yr^{-1} (0.24 Mg C ha^{-1} yr^{-1}) with the application of 96 lb N acre^{-1} yr^{-1} (Fig. 7). This calculation assumed a C cost of 1.23 lb C lb^{-1} N fertilizer for the manufacture, distribution, and application of fertilizer N (Izaurralde et al., 1998). Assuming that the application of N fertilizer would also lead to increased nitrous oxide (N_2O) emission, which has 296 times the global warming potential of CO_2 (IPCC, 1997), net C offset from N fertilization would be maximized at 63 lb acre^{-1} yr^{-1} (0.07 Mg C ha^{-1} yr^{-1}) with the application of 21 lb N acre^{-1} yr^{-1}. These calculations suggest a positive, but diminishing return of investment with increasing application of N fertilizer, regarding mitigation of greenhouse gas emission.

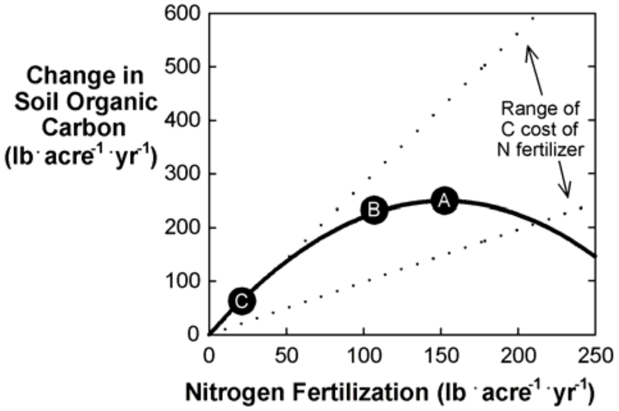


Figure 7. Change in soil organic C (heavy line) with application of N fertilizer averaged across 6 studies in the southeastern USA. Dotted lines represent C cost of N fertilizer at the minimum rate of 0.98 kg C kg^{-1} N for manufacture, distribution, and application (West and Marland, 2002) and a maximum rate of 2.82 lb C lb^{-1} N to include additional C equivalent due to nitrous oxide emission (IPCC, 1997). Point A represents maximum soil organic C sequestration of 250 lb acre^{-1} yr^{-1} without considering the C cost of N fertilizer. Point B represents optimum soil organic C sequestration of 230 lb acre^{-1} yr^{-1} to achieve maximum C offset using the minimal C cost of N fertilizer application. Point C represents optimum soil organic C sequestration of 63 lb acre^{-1} yr^{-1} to achieve maximum C offset assuming the maximum C cost of N fertilizer application. From Franzluebbers (2005) with data to derive response curve from Franzluebbers et al. (1994, 1995), McCarty and Meisinger (1997), Potter et al. (1998), Sainju et al. (2002), and Siri-Prieto et al. (2002).

Nutrients from animal manure (e.g., poultry litter, confined dairy, or beef cattle) represent valuable agricultural resources that are not currently widely and fully utilized. Georgia and bordering states produce about 42% of the poultry in the USA, but only a small percentage of the litter is utilized as fertilizer in cropland. Nyakatawa et al. (2001) suggested that poultry litter application to cropping systems with winter annual cover crops could be an environmentally suitable practice to reduce reliance on commercial fertilizer and dispose of large quantities of waste from a burgeoning

poultry industry. Endale et al. (2002) found that combining no tillage with poultry litter application produced up to 50% greater cotton lint than conventionally tilled and fertilized cotton in the Southern Piedmont. Parker et al. (2002) reported 7 to 20% greater organic C in the surface 2” (5 cm) of soil in a cotton/rye (*Secale cereale* L.) cropping system with poultry litter than with commercial fertilizer application in the Tennessee Valley. Application of dairy manure increased soil organic C 1.2 ton acre^{-1} in a cotton-corn rotation with cover crops in the Coastal Plain (J. Terra, unpublished data). The limited studies conducted on animal manure application to cotton production systems suggest that both yield and soil organic C sequestration can be increased. More research is urgently needed to investigate the effect of animal manure application on soil organic C sequestration, yield potential and quality characteristics, and nutrient leaching and runoff in various cotton production systems, especially in intensive crop rotations with cover crops. The widespread availability of poultry litter, dairy manure, and swine effluent in the region dictates a need for greater understanding of how nutrients can be recycled among agricultural enterprises more effectively to meet production and environmental goals.

4.4. Sod-Based Crop Rotation

Soil organic C sequestration under grass management systems in the southeastern USA can exceed sequestration rates observed under crop management systems. From 12 observations of various grass establishment studies, soil organic C sequestration was 920 lb acre^{-1} yr^{-1} (1.03 ± 0.90 Mg C ha^{-1} yr^{-1}) during an average of 15 years of investigation (Franzluebbers, 2005). Rotation of crops with pastures could take advantage of high soil organic C and promote higher productivity under ideal conditions, because (1) surface soil would be enriched in soil organic matter and organically bound nutrients, (2) some weed pressures could be reduced, (3) soil water storage could be enhanced, and (4) disease and pest pressures could be reduced. Successful crop and pasture rotation systems have been developed with conservation tillage in South America (Diaz-Zorita, 2002; Garcia-Prechac et al., 2004). These studies have demonstrated that soil organic C can be preserved following rotation of pasture with crops when using conservation tillage. Although some soil physical limitations can develop under heavily trafficked pastures, the accumulation of soil organic C at the surface can buffer this impact (Franzluebbers et al., 2001).

Under a variety of crop rotations at the Wiregrass Research and Extension Center in Alabama, highest concentration of soil organic C was found for peanut (*Arachis hypogaea* L.) rotated with 4 years of bahiagrass (*Paspalum notatum* Fluegge) (0.54%) and peanut rotated with 2 years of bahiagrass (0.52%) (J. Shaw, unpublished data). Lowest soil organic C concentration was found for continuous peanut (0.39%) and peanut-fallow (0.40%). This experiment also showed that irrigation increased soil organic C concentration by 37%. At the same location, soil organic C concentration of the surface 2” (5 cm) in a long-term cotton-peanut rotation (initially 0.76%) increased to 0.94% (9.4 g kg^{-1}) following introduction of winter annual pasture

[oat (*Avena sativa* L.) or ryegrass (*Lolium multiflorum* Lam.)] for three years (G. Siri-Prieto, unpublished data).

Much more research is needed to determine the potential for soil organic C sequestration and crop productivity under sod-based crop rotation systems in the region, especially under conservation tillage. We suggest that there is great potential for crop-pasture rotation systems to improve soil and water quality and crop productivity. Income and labor diversity could be either bane or blessing, depending upon specific circumstances producers face. Scientifically, however, sod-based crop rotations make a great deal of agronomic and environmental sense.

5. Predicting Soil Organic C Changes in Cotton Production Systems

The Soil Conditioning Index (SCI) is a tool currently used by the USDA-Natural Resources Conservation Service to predict changes in soil organic C (Fig. 8), as affected by cropping system, tillage management, and soil texture (Hubbs et al., 2002). The SCI has been incorporated into the Revised Universal Soil Loss Equation (RUSLE2) to assist district staff members of the Natural Resources Conservation Service working with local producers to plan and design crop and residue management practices for overcoming issues of low soil organic matter, poor soil tilth, and other soil quality-related problems. When SCI is negative, soil organic C is predicted to decline. When SCI is positive, soil organic C is predicted to increase. The magnitude of the SCI value is more related to the probability of achieving a change rather than determining an absolute value of that change. The SCI is being used by the Natural Resources Conservation Service to calculate payments to landowners enrolled in the Conservation Security Program.

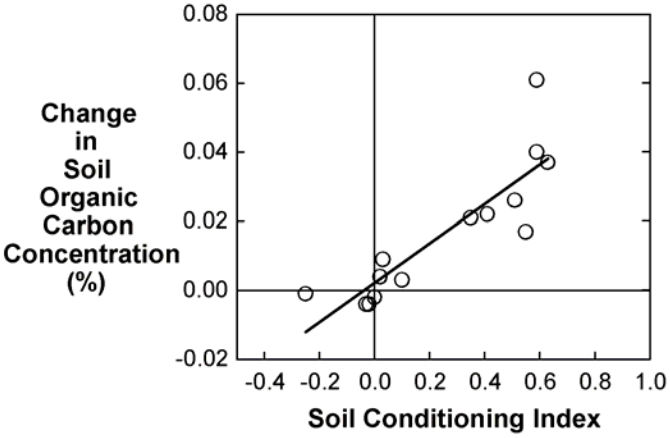


Figure 8. Relationship of soil organic C with the soil conditioning index. Reproduced from Hubbs et al. (2002) with data in eastern USA from Edwards et al. (1992), Hendrix (1997), Hunt et al. (1996), Ismail et al. (1994), and Mahboubi et al. (1997).

In the following sections, we present some scenarios of common crop and tillage management systems being used in the major land resource areas of the southeastern USA. All cropping systems include cotton as a primary crop, either in monoculture or in rotation with other common crops of the region.

5.1. Appalachian Ridges and Valleys (Tennessee Valley)

Continuous cotton production in the Tennessee Valley of northern Alabama would cause loss of soil organic C under both chisel plow and conservation tillage (Table 3), although the extent of loss would likely be greater with inversion tillage than with conservation tillage. By including a cover crop in a cotton-corn rotation, soil organic C would more likely increase, especially with application of poultry litter as a nutrient source. Even with soil disturbance with paratill prior to cotton planting, including a cover crop in the cropping system could help to promote soil organic C sequestration.

Soil compaction can be a problem in the Tennessee Valley region, where soils have platy structure, leading to high penetration resistance, especially under no tillage. Cotton yield reductions were common under no tillage and jeopardized the adoption of this technology in the early 1990s when the common practice was to plant without tillage directly into cotton stubble with no winter cover crop. It was later demonstrated that non-inversion tillage under the row in the autumn coupled with a rye cover crop to reduce compaction and provide moisture-conserving surface residue could increase yield (Raper et al. 2000a, b; Schwab et al., 2002). This situation is in accordance with the last scenario in Table 3, where paratill prior to cotton reduced the SCI compared to no paratill, but the SCI was still positive.

Table 3. Management scenarios and soil conditioning index (SCI) for the Appalachian Ridges and Valleys region.

Location	Soil Series	Soil Texture[*]	Slope (%)	Scenario	SCI
Belle Mina AL	Decatur	SiL	3	Continuous cotton, fall chisel plow	-2.60
				Continuous cotton, no tillage	-0.36
				Cotton/rye cover-corn/rye cover	0.17
				Cotton/rye cover-corn/rye cover, 5 ton/acre poultry litter prior to cotton	0.21
				Cotton/rye cover-corn/rye cover, paratill prior to cotton	0.09

[*] SiL is silt loam.

5.2. Coastal Plain

All conventional-tillage scenarios in the Coastal Plain region would cause loss of soil organic C (Table 4). Soil management strategies to increase soil organic C sequestration included the use of conservation tillage, greater cropping diversity with high residue-producing crops such as corn and cover crops, application of animal manure, and inclusion of sod-based rotations. Subsoiling with paratill has been found to help alleviate soil compaction due to traffic and natural reconsolidation, which can constrain root grow in many Coastal Plain soils. However when paratill was simulated in monoculture cotton with conservation-tillage planting at Shorter AL, soil organic C was predicted to decline. Only in a cotton-corn rotation was SCI positive when paratill was performed.

Table 4. Management scenarios and soil conditioning index (SCI) for the Coastal Plain region. CT is conventional tillage and NT is no tillage.

Soil Series	Slope (%)	Soil Texture[*]	Location / Scenario	SCI		
				Monoculture Cotton		Rotated Cotton[**]
				CT	NT	NT
Bendale	2	SL	Brewton AL,no manure, no paratill	-1.2	0.21	0.50
Norfolk	3	LS	Florence SC, no manure, no paratill	-0.41	0.44	0.60
	4	LS	Goldsboro NC, no manure, no paratill	-0.62	0.31	0.58
Dothan	2	SL	Headland AL, no manure, no paratill	-0.94	0.23	0.54
			grazed annual ryegrass, no paratill			0.42
			grazed annual ryegrass, with paratill			0.12
Bama	2	SL	Shorter AL, no manure, no paratill	-0.84	0.28	0.54
			With manure, no paratill	-0.63	0.47	0.60
			No manure, with paratill	-0.84	-0.27	0.45
			Intensive rotation[***], no paratill			0.65
			Intensive rotation[***], with paratill			0.56

[*] LS is loamy sand, SL is sandy loam.

[**] Base rotation is cotton / rye cover – corn / rye cover

[**] Similar rotation to that described in Reeves and Delaney (2002): corn / sun hemp cover / wheat – cotton / white lupin (*Lupinus albus* L.) + crimson clover (*Trifolium incarnatum* L.) cover.

5.3. Mississippi Valley: Silty Uplands and Alluvium Land Areas

All conventional-tillage scenarios in the Mississippi Valley region would cause loss of soil organic C (Table 5). Steep slope in Senatobia MS contributed to the large negative SCI under conventional tillage and smaller negative SCI even under no tillage. With silt loam texture of soils in the region, these soils are highly susceptible to C loss by erosion. Conservation tillage and rotation of cotton with high residue-input crops such as corn and cover crops are key management tools for maintaining adequate infiltration and reducing soil erosion. Mutchler et al. (1985) measured 33 ton acre^{-1} yr^{-1} (74 Mg ha^{-1} yr^{-1}) of soil loss from conventional-tillage cotton, but only 5 ton acre^{-1} yr^{-1} (10 Mg ha^{-1} yr^{-1}) of soil loss from reduced-tillage and no-tillage cotton.

Triplett et al. (1996) determined the influence of four consecutive years of conventional tillage, ridge tillage, minimum tillage and no tillage on cotton yield on silty upland soils of the Mississippi Valley. Seed-cotton yield was greatest under conventional tillage during the 1st year, but was greatest under no tillage compared with all other tillage systems during the 2nd through 4th years. These data suggest that the benefits of conservation tillage on productivity and soil organic C can be successfully developed with time due to a change in soil physical, chemical, and biological properties.

Table 5. Management scenarios and soil conditioning index (SCI) for the Mississippi Valley region. CT is conventional tillage and NT is no tillage.

				SCI		
				Monoculture Cotton		Rotated Cotton **
Soil Series	Slope (%)	Soil Texture *	Location	CT	NT	NT
Grenada	5	SiL	Senatobia MS	-8.4	-1.9	0.07
Gigger	2	SiL	Winnsboro LA	-1.9	0.03	0.11
Dundee	2	SiL	Stoneville MS	-1.9	0.36	0.42
Commerce	2	SiL	St. Joseph LA	-1.5	0.08	0.52

* SiL is silt loam. ** Cotton / wheat cover – corn / wheat cover

5.4. Southern Piedmont

All conventional-tillage scenarios in the Southern Piedmont region would cause loss of soil organic C (Table 6). Monoculture cotton production with conservation tillage would increase soil organic C, but including a winter cover crop or grain in the rotation would enhance soil organic C sequestration even further. Increasing crop rotation complexity with short-term sod would have high potential for soil organic C sequestration. In the Southern Piedmont, cotton was the dominant crop for more than 150 years and soil erosion scars in this sloping physiographic region suggest that crop residues were poorly managed for as long (Langdale et al., 1994). Despite adequate rainfall, high water runoff and crusting contribute to low soil water storage under conventional tillage. Hence, maintaining sufficient residue cover is particularly important for reducing surface sealing, water runoff, soil loss, and runoff of agricultural chemicals (Raczkowski et al., 2002). Research on these soils has demonstrated that conservation tillage leads to greater soil organic C storage, improvement in soil quality, and greater cotton yield (Franzluebbers et al., 1999; Schomberg et al., 2003). Deep tillage (such as subsoiling without inversion of soil) may be required only initially during transition to conservation tillage management to overcome the lack of soil structure following decades of intensive tillage.

Table 6. Management scenarios and soil conditioning index (SCI) for the Piedmont region.

Location	Soil Series	Soil Texture	Slope (%)	Scenario	SCI
Watkinsville GA	Cecil	SL	4	Monoculture cotton, spring-chisel tillage	-1.10
				Monoculture cotton, fall-chisel tillage	-1.80
				Monoculture cotton, no tillage	0.12
				Cotton / rye cover, no tillage	0.36
				Cotton – corn – corn – tall fescue pasture (3years)	0.61
Auburn AL	Marvyn	LS	3	Monoculture cotton, fall-disk tillage	-0.82
				Monoculture cotton, no tillage	0.27
				Cotton / grazed rye cover, no tillage	0.42
				Cotton / wheat, no tillage	0.69

[*] LS is loamy sand, SL is sandy loam.

5.5. Eastern Texas: Blackland Prairie, Gulf Coast Prairies, and Lower Rio Grande Plain Land Areas

All conventional-tillage scenarios in the eastern Texas region would cause loss of soil organic C (Table 7). Adoption of conservation tillage would enhance soil organic C in these fine-textured soils. Rotating cotton with corn using conservation tillage would lead to even greater potential for soil organic C sequestration. The relatively small difference between monoculture cotton and rotated cotton using conservation tillage is probably because no cover crop was simulated. Although the drier climatic condition in this region might limit the successful incorporation of a cover crop in the rotation, efforts to develop this technology would probably be beneficial for potential soil organic C sequestration.

Table 7. Management scenarios and soil conditioning index (SCI) for the eastern Texas region.

Soil Series	Slope (%)	Soil Texture[*]	Location	Scenario		
				Monoculture Cotton		Rotated Cotton[**]
				CT	NT	NT
Houston Black	2	C	Temple TX	-1.10	0.55	0.53
Orelia	2	CL	Corpus Christi TX	-0.71	0.26	0.36
Hidalgo	2	SCL	Weslaco TX	-0.70	0.41	0.51

[*] C is clay, CL is clay loam, SCL is sandy clay loam.
[*] Base rotation is cotton – corn.

6. Politics and Programs to Foster Soil Organic C Sequestration

Although the USA has not ratified the Kyoto Protocol, sufficient political pressure exists to reduce or mitigate greenhouse gas emissions. In February 2002, the USDA received specific instructions from President Bush to design incentives for landowners to adopt production practices and land uses that increase C sequestration. The Bush administration has committed to reduce greenhouse gas emission intensity (i.e., emission per unit of economic activity)18% by 2012 (Hayes and Gertler, 2002). This goal consists of a voluntary program criticized by some environmentalists, who advocate a mandatory system. Since multinational corporations face emission caps for their operations in Kyoto-ratifying countries, the uncertainty of future emission caps in the USA place business assets at risk and have stimulated a private market for C trading. Current indications are that a mandatory greenhouse gas emission cap would unlikely be legislated in the USA (Young, 2003).

Currently, there are two reasonable scenarios in which farmers in the USA might be additionally compensated for the environmental service of soil organic C sequestration. Producers should foremost recognize that it is in their own economic and ecological interests to harvest the productivity profits and foster a stewardship ethic by managing their farms to increase soil organic C. One compensation scenario is through government incentives and the other is through a private trading market that allows emitters to buy offset credits from sequesters.

6.1. Government Incentive Programs

Current government incentive programs do not specifically address C sequestration, but some programs authorized under the Farm Security and Rural Investment Act (i.e., 2002 Farm Bill) recommend specific practices that would be complementary to the goals of soil organic C sequestration. The following two programs are administered by the USDA–Natural Resources Conservation Service (www.nrcs.usda.gov) and indirectly address soil C sequestration in agricultural production systems.

Environmental Quality Incentives Program (EQIP)

Reauthorized in the 2002 Farm Bill, this program provides financial and technical assistance to farmers and ranchers who adopt environmentally sound practices on eligible agricultural land. National priorities addressed by EQIP are:

- reduction of non-point source pollution such as nutrients, sediment or pesticides
- reduction of groundwater contamination
- conservation of ground and surface water resources
- reduction of greenhouse gas emissions
- reduction in soil erosion and sedimentation from unacceptable levels on agricultural land
- promotion of habitat conservation for at-risk species

EQIP offers contracts with a minimum term that ends one year after the implementation of the last scheduled practice and a maximum term of 10 years. Contracts provide incentive payments and cost-sharing to implement conservation practices subject to technical standards adapted for local conditions.

Conservation Security Program (CSP)

This voluntary program provides financial and technical assistance to agricultural producers who conserve and improve the quality of soil, water, air, energy, plant and animal life, and support other conservation activities. Soil and water quality practices include conservation tillage, crop rotation, cover cropping, grassed waterways, wind barriers, and improved nutrient, pesticide, or manure management. Maximum annual payments vary from $20,000 to $45,000, depending on the tier of participation. Contracts are valid for 5 to 10 years.

In fiscal year 2004, the CSP provided funding to 18 watersheds in the USA. About 27,300 farms and ranches were within these watersheds, covering 5.7 Mha (14 million acres). In the southeastern USA, three watersheds were targeted: (1) Hondo River in Texas, (2) Little River in Georgia, and (3) Saluda River in South Carolina. The program has been expanded to more watersheds in 2005 (Fig. 9). An enrolled landowner in one of these watersheds would receive a payment of the SCI value for practices employed times $11.60 acre^{-1}, up to a maximum SCI value of 2.5. Cotton farmers using conservation tillage could be expected to receive anywhere from no payment to $8 acre^{-1} with an average of $3.36 acre^{-1} based on SCI values derived from Tables 3-7.

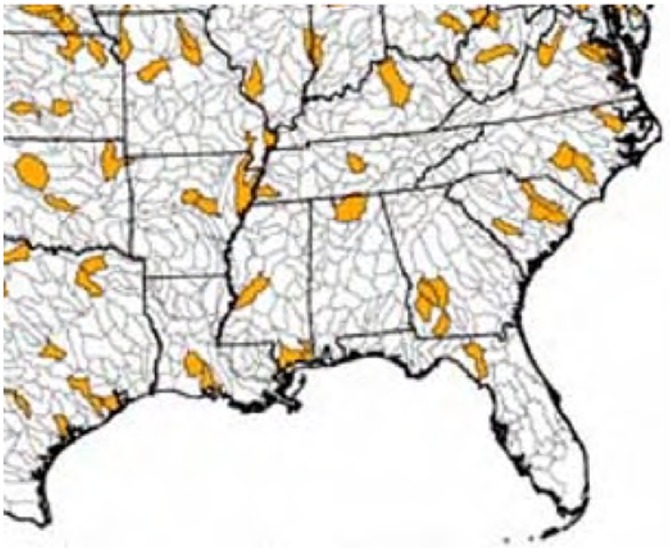


Figure 9. Watersheds in the southeastern USA targeted for CSP enrollment in 2005 by the USDA-Natural Resource Conservation Service (see information at www.nrcs.usda.gov/programs/csp).

6.2. Carbon Trading Market

A strategy to capitalize on the emission and sequestration of greenhouse gases could take the form of a C trading market (Scott et al., 2004). Trading of emission permits and credits would likely be brokered by intermediaries of emitters and sequesters. Although this paper is concerned with soil organic C sequestration, it is noteworthy that in a market economy, several factors (e.g., quantity, price, permanence, etc.) will dictate from whom a buyer might trade. The supply of C credits may come from a variety of sources. For example, a power plant may switch from coal to biofuel to offset CO_2 emission or may decide to sequester CO_2 mechanically (i.e., pipe CO_2 produced into geologic formations or the ocean) rather than purchase credits from soil organic C sequestration.

Emission of CO_2 in the USA is derived primarily from fossil-fuel combustion, accounting for 97% of total emission in 2001 [5.3 billion tons (4.8 Pg) of CO_2 equivalent]. Most petroleum was consumed for electricity generation, transportation, and industrial activity (Fig. 10).

Most analyses highlight the biophysical potential of soil organic C sequestration under a variety of management scenarios (Lal, 1997; Follett, 2001; West and Post, 2002; Sperow et al., 2003).

All agree that more widespread adoption of conservation management practices could greatly increase the quantity of soil organic C currently being sequestered. Sperow et al. (2003) estimated the present rate of soil organic C sequestration in cropland of the USA at 19 million tons yr^{-1} (17 Tg C yr^{-1}). With complete adoption of no-tillage management on all currently cropped land (319 million acres), soil organic C sequestration could increase to 52 million tons yr^{-1} (47 Tg C yr^{-1}).

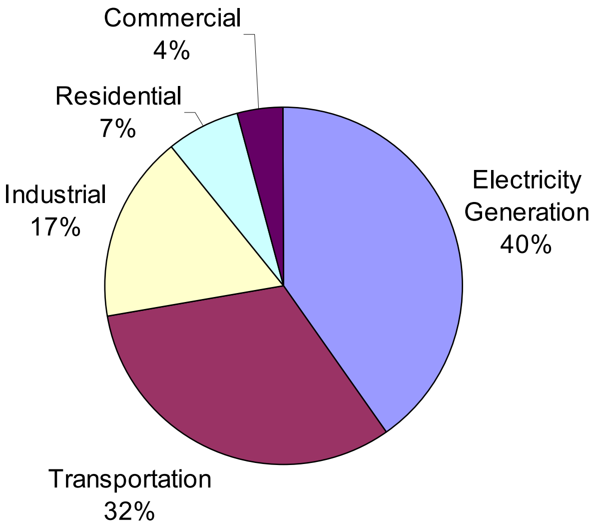


Figure 10. Sources of CO_2 emission in the USA (US-EPA, 2003).

Since the marginal cost of sequestering increasingly greater quantities of C rises, the likelihood of purchasing higher-cost credits for soil organic C sequestration will increase in the future. Lewandrowski et al. (2004) evaluated the potential farm sector impacts of various strategies to sequester C in agricultural soil and plant biomass components. Changes in agricultural management (e.g., expanding land area under no tillage or shifting to more diverse and higher residue-producing crop rotations) are more likely to occur at very low C credit prices, but afforestation may become the dominant sequestration activity at prices >\$18 ton^{-1} (\$20 Mg^{-1} C). McCarl and Schneider (2001) suggested that giving landowners greater flexibility to choose the strategy most suitable to regional characteristics might facilitate acceptance of policies to encourage adoption of agricultural and forestry practices to mitigate greenhouse gas emission.

The magnitude of uncertainty associated with a possible limit on greenhouse gas emission has drawn the attention of both sides of a C market trading system. The interest of energy industries in a C trading system could also be linked to a desire to project a positive image to the public of their concern for environmental health. Another interest of participants might be to explore business opportunities at a currently lower cost in anticipation of future emission caps. The opportunities for farmers to benefit from a trading system with credits derived from soil organic C sequestration will depend on the demand for and competitiveness of C credits and the future roles of aggregators and government programs.

The Chicago Climate Exchange (CCX) (http://www.chicagoclimatex.com) is a pilot greenhouse gas trading venue. Its members include (1) corporations, municipalities, and other entities that emit greenhouse gases from facilities in the USA, Canada, and Mexico, (2) entities that have small or no direct greenhouse gas emissions, but are committed to comply with CCX rules by offsetting the greenhouse gas emissions associated with business-related activities, and (3) project owners and executors, registered aggregators, and entities selling exchange offsets. Participants that buy C credits have made a voluntary, legally binding commitment to reduce greenhouse gas emission by 2006 (final year of the pilot program) to 96% of their 1998-2001 baseline.

The Iowa Farm Bureau (http://www.iowafarmbureau.com) is working to aggregate credits from soil organic C sequestration for sale on the CCX. Additional credits are targeted for methane capture and reduced N fertilizer application as mechanisms of mitigating greenhouse gas emission. To be eligible for Exchange Soil Offset (XSO), the land must be under continuous conservation tillage (no till, strip till, or ridge till) and must not have soybean planted for more than two years. XSOs have been issued at the rate of 300 lb C acre^{-1} yr^{-1} (0.34 Mg CO_2-C ha^{-1} yr^{-1}) for commitment to conservation tillage and 450 lb C acre^{-1} yr^{-1} (0.51 Mg CO_2-C ha^{-1} yr^{-1}) for commitment to perennial grass cover. Transfer price of XSOs would be the sales price as determined by sale through the CCX less a 10% service fee. Weighted average price has been \$2.80 to \$3.25 ton^{-1} C (\$3.08 to \$3.59 Mg^{-1} CO_2-C) (Sandor, 2003).

Considering the average soil organic C sequestration rate of 430 lb C acre^{-1} yr^{-1} (0.48 Mg C ha^{-1} yr^{-1}) for conservation-tillage cotton production systems in the southeastern USA (Table 2) and the average price of a C credit on the CCX at \$3.00 ton^{-1} CO_2-C, a cotton producer in the southeastern USA might expect to receive \$0.65 acre^{-1} yr^{-1} (\$1.44 ha^{-1} yr^{-1}), assuming soil organic C sequestration credits could be aggregated and sold today. Important to note is that selling C credits would not prevent producers from getting additional income from government incentive programs (CSP or EQIP). With current information, a cotton producer could expect to get a lower payment from a C credit market than from land enrolled in CSP.

The currently low prices of C credits in the USA are a consequence of a voluntary market trading system. If emission caps were to be enforced, C credit prices would certainly rise. In the emission trading scheme of the Kyoto Protocol (www.co2e.com), trades have been few and far between at current prices of about \$17 ton^{-1} (\$19 Mg^{-1} CO_2-C).

7. Summary and Conclusions

Global atmospheric CO_2 concentration has been increasing steadily in the past century and the scientific community has linked this increase in greenhouse gas emission to potential global warming. Carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) are three greenhouse gases that are derived from agricultural operations. Two primary reasons for the recent imbalance in the atmosphere are: (1) land-use change associated with the historical cultivation of native areas that released CO_2 from burned vegetation and exposed soil and (2) an ever increasing rate of fossil-fuel combustion.

Current and future agricultural management systems could help to mitigate greenhouse gas emission by sequestering greater quantities of carbon (C) in soil organic matter with the adoption of conservation practices. A review of literature in cotton production systems in the southeastern USA indicates that soil organic C could be sequestered at an average rate of 430 lb acre^{-1} yr^{-1} with no-tillage management. Available data suggested that soil organic C sequestration would be twice as high by combining no-tillage management with cover cropping (600 lb acre^{-1} yr^{-1}) than simply no-tillage management without a cover crop (300 lb acre^{-1} yr^{-1}). More diverse crop rotations of cotton with high-residue-producing crops such as corn and small grains would lead to greater soil organic C sequestration. Animal manure application to cotton production systems could also stimulate an increase in soil organic C by providing nutrients and C substrates. The effects of crop rotation and manure applications require more research, since conclusions were drawn from only a handful of actual field studies.

Using the Soil Conditioning Index (SCI) to predict changes in soil organic C, all cotton cropping systems with conventional tillage would lead to loss of soil organic C. Growing cotton in monoculture with no tillage could lead to a small loss, no change, or a small increase in soil organic C, depending upon Major Land Resource Area, slope, and soil texture. The SCI predicted larger changes in soil organic C whenever no-tillage management was combined with cover cropping and cotton was rotated with high-residue-producing crops. The SCI will be used to determine payments to farmers enrolling in the Conservation Security Program, administered by the USDA–Natural Resources Conservation Service. Cotton producers in eligible watersheds could expect to receive an average of \$3.36 acre^{-1}, with payments up to \$8 acre^{-1}, depending on practices employed and soil conditions.

Open-market trading of C credits has been developed by the Chicago Climate Exchange. Current C credits are being traded at \$3 ton^{-1} of C. Cotton production systems managed with conservation tillage could expect to yield less than \$1 acre^{-1}, although prices would be sensitive to world market developments and adoption of U.S. government polices to cap greenhouse gas emissions. For countries that have agreed to limit greenhouse gas emissions through the Kyoto Protocol, C credits are currently being traded for about \$17 ton^{-1} of C. Soil organic C sequestration in typical cotton production systems in the southeastern USA would yield about \$4 acre^{-1} under these higher prices.

This report has demonstrated that conservation practices that include appropriate tillage and crop rotations can lead to significant soil organic C accumulation. Soil organic C is important to maintain high soil quality, to improve crop productivity, and to mitigate greenhouse gas emission. Further agricultural research and extension activities are needed to capture the full benefits of soil organic C sequestration for agronomic, environmental, and economic sustainability.

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