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Soil Organic Carbon Sequestration in Cotton Production Systems of the Southeastern United States: A Review

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ABSTRACT

Past agricultural management practices have contributed to the loss of soil organic carbon (SOC) and emission of greenhouse gases (e.g., carbon dioxide and nitrous oxide). Fortunately, however, conservation-oriented agricultural management systems can be, and have been, developed to sequester SOC, improve soil quality, and increase crop productivity. Our objectives were to (i) review literature related to SOC sequestration in cotton (*Gossypium hirsutum* L.) production systems, (ii) recommend best management practices to sequester SOC, and (iii) outline the current political scenario and future probabilities for cotton producers to benefit from SOC sequestration. From a review of 20 studies in the region, SOC increased with no tillage compared with conventional tillage by 0.48 ± 0.56 Mg C ha^{-1} yr^{-1} (H_0: no change, $p < 0.001$). More diverse rotations of cotton with high-residue-producing crops such as corn (*Zea mays* L.) and small grains would sequester greater quantities of SOC than continuous cotton. No-tillage cropping with a cover crop sequestered 0.67 ± 0.63 Mg C ha^{-1} yr^{-1}, while that of no-tillage cropping without a cover crop sequestered 0.34 ± 47 Mg C ha^{-1} yr^{-1} (mean comparison, p = 0.04). Current government incentive programs recommend agricultural practices that would contribute to SOC sequestration. Participation in the Conservation Security Program could lead to government payments of up to \$20 ha^{-1}. Current open-market trading of C credits would appear to yield less than \$3 ha^{-1}, although prices would greatly increase should a government policy to limit greenhouse gas emissions be mandated.

Concentration of CO_2 in the atmosphere has increased from 280 ppmv (parts per million by volume) during preindustrial times to about 375 ppmv in 2002 at Mauna Loa Observatory, Hawaii, with most of the increase during the past 50 yr a result of fossil-fuel burning (Intergovernmental Panel on Climate Change, 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, nitrous oxide, ozone, and chlorofluorocarbons) on global warming and climate change (U.S. Global Change Research Program, 2004).

Greatest mitigation of rising CO_2 concentration would be attained with a 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 (Wofsy and Harriss, 2002). Either increasing photosynthesis or decreasing respiration 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 (USDA Office of the Chief Economist, 2004). Landowners and agricultural producers who 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.

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). Most analyses highlight the biophysical potential of SOC 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 SOC currently being sequestered. Sperow et al. (2003) estimated the present rate of SOC sequestration in cropland of the United States at 17 Tg C yr^{-1}. With complete adoption of no-tillage management on all currently cropped land (129 Mha), SOC sequestration could increase to 47 Tg C yr^{-1}.

Agriculture and forestry in the United States directly emit 8% of the total greenhouse gas (GHG) emission of the nation (USDA Office of the Chief Economist, 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 unaccounted potential sinks suggest that agriculture and forestry could act as key components to reduce the nation's burden of GHG emission (USDA Office of the Chief Economist, 2004). Agricultural activities could mitigate GHG emission by (i) direct emission reduction, for example, lower fossil-fuel consumption with fewer field passes using conservation tillage, (ii) sequestering C in plant biomass and soil organic matter, (iii) producing biofuels that would substitute for fossil fuels, and

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Abbreviations: GHG, greenhouse gas; SOC, soil organic carbon.

(iv) 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 to maximize return from N inputs.

Soil organic C is 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). Pasture 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). Pasture-based crop rotations with conservation tillage could be an innovative use of an historical conservation technology for increasing SOC sequestration in cropland (Studdert et al., 1997; Diaz-Zorita et al., 2002; Garcia-Prechac et al., 2004).

Soil organic C should not only be viewed as a C pool to mitigate atmospheric carbon dioxide concentration, but also an important component that contributes to a wide variety of key soil functions (Doran et al., 1994). Soil organic C is strongly related to how effectively soil functions as a medium for plant growth, regulates and partitions water flow in the environment, and serves as an environmental buffer to the numerous natural and xenobiotic compounds presented to the environment. Soil organic C controls many other soil properties, including aeration, soil structure, cation exchange capacity, available water capacity, nutrient cycling, and soil biological diversity.

Our objectives were to (i) review published and unpublished scientific literature related to SOC sequestration in cotton production systems of the southeastern United States, (ii) recommend best management practices to sequester SOC in cotton production systems, and (iii) outline the current political scenario and future probabilities for cotton producers to benefit from SOC sequestration.

THE SOUTHEASTERN UNITED STATES

For the purposes of this paper, we define the southeastern United States 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 14°C in the northern sections to 25°C in the southern sections. Mean annual precipitation typically exceeds 1000 mm throughout the region, but is highest along the coastlines and in the central section (>1400 mm).

Although soils in the southeastern United States typically have relatively low organic C compared with other parts of North America (Jenny, 1930), the potential for significant SOC 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 SOC 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 tree plantings. 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 SOC. The diversity of land use and the potential for flexible land-use rotation due to favorable climatic conditions offer agricultural producers in the southeastern United States more opportunities to maximize soil C sequestration than in other regions.

Surface residue management is especially critical in the southeastern United States, because soils are highly erodible and high-energy rainstorms occur during the growing season (Blevins et al., 1994). Soils of the region have low 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 SOC with time (Hendrix et al., 1998). Fortunately, however, conservation management that limits soil disturbance can restore SOC, mainly near the surface. Soil organic C is typically very low below a 0.5-m depth in most soils of the region, irrespective of management (Franzluebbers, 2005).

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 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 toward 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. Differences in adoption among states could be because (i) adoption has been greatest in areas with historically severe erosion problems, (ii) producers on more fertile bottomland soils have not seen the need for change, and (iii) leadership and promotion have varied by extension agencies. The relatively low current adoption rate suggests great potential for further adoption of conservation management technologies that could both sequester SOC and increase productivity.

Fig. 1. The southeastern United States with delineation of major land resource areas and locations where research on soil organic C with conservation tillage in cotton production systems described in Table 2 has been determined.

MANAGEMENT STRATEGIES TO SEQUESTER SOIL ORGANIC CARBON

Conservation Tillage

Conventional tillage buries residues, disrupts macroaggregates, increases aeration, and stimulates microbial breakdown of SOC (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 SOC near the surface. Plant residues decompose slower on the soil surface

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

	Land in cotton		Tillage system of land in cotton					
			Conservation tillage					
State	Total	% of total cropland	No-till	Ridge-till	Mulch-till	Total	Reduced tillage	Conventional tillage
	Mha	%						
Alabama	0.22	33	51	4	2	58	16	26
Arkansas	0.35	13	8	9	8	25	21	54
Florida	0.04	7	29	8	26	63	3	34
Georgia	0.53	39	40	0	1	41	12	47
Louisiana	0.19	15	10	16	3	29	40	31
Mississippi	0.44	28	24	1	1	26	21	53
North Carolina	0.30	17	41	2	0	43	17	40
South Carolina	0.09	15	46	1	0	47	8	45
Tennessee	0.21	17	46	0	0	47	8	45
Texas (eastern)	0.41	22	1	0	2	3	19	78
Virginia	0.08	5	71	0	4	75	7	18
Southeastern United States	2.86	24	28	3	2	34	17	49

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 SOC, while at the same time increasing cotton lint and seed yield (Triplett et al., 1996). Yield benefits of conservation tillage have not always been observed, especially in 1- to 2-yr studies. The benefit of conservation tillage will often be expressed most significantly in long-term evaluations (Franzluebbers, 2005).

Average SOC sequestration with adoption of conservation tillage was 0.48 Mg C ha^{-1} yr^{-1} (H_0: no change, $p < 0.001$) (Table 2). This rate of SOC sequestration for the southeastern United States is nearly identical to an assumed value of 0.5 Mg C ha^{-1} yr^{-1} used by Lal et al. (1998) for the entire United States. From 96 observations of all cropping systems in the southeastern United States, Franzluebbers (2005) reported SOC sequestration of 0.42 ± 0.46 Mg C ha^{-1} yr^{-1}. West and Post (2002) calculated average SOC sequestration of 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 SOC sequestration estimates from conservation-tillage management systems in other regions of the world include: 0.48 ± 0.59 Mg C ha^{-1} yr^{-1} in the central United States (Johnson et al., 2005), 0.30 ± 0.21 Mg C ha^{-1} yr^{-1} in the southwestern United States (Martens et al., 2005), 0.27 ± 0.19 Mg C ha^{-1} yr^{-1} in the northwestern United States and western Canada (Liebig et al., 2005), 0.25 ± 0.45 Mg C ha^{-1} yr^{-1} in Brazil (Zinn et al., 2005), and 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 having the highest SOC sequestration potential with adoption of conservation tillage that included the central and upper southeastern U.S. regions. Clearly, adoption of conservation tillage in the southeastern United States has the potential for some of the highest rates of SOC sequestration in North America. Greater adoption of this technology will be advantageous to producers and society in reaping the multiple benefits of C storage in soil.

Although these data on SOC sequestration in cotton production systems in the southeastern United States represent a great deal of research effort, the diversity in estimates points to a deficiency in obtaining an unequivocal estimate of potential SOC 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 SOC 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 SOC sequestration under a wider range of soil conditions in crop rotations that reflect high economic return and stewardship of land, and that minimize the impact on the environment.

Crop Rotation and Cover Cropping

Residue management is a key component in sequestering SOC in cotton production systems, because of cotton's 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 SOC under cotton production in the southeastern United States is rather scarce. The "Old Rotation" experiment at Auburn University was initiated in 1896 to determine (i) the effect of rotating cotton with other crops to improve yields and (ii) the effect of winter legumes in cotton production systems (Mitchell and Entry, 1998). Cotton seed yield during a 10-yr period from 1986–1995 was greater in rotation with corn and winter legumes than under monoculture cropping. Mitchell and Entry (1998) demonstrated a positive association of SOC with cotton seed yield, suggesting that higher biomass inputs from cover crops and corn in rotation with cotton improved SOC sequestration and cotton productivity. With 98 yr of cultivation, 2- and 3-yr rotations of cotton with corn and soybean [*Glycine max* (L.) Merr.] resulted in SOC concentration of 10 g C kg^{-1}, while SOC under continuous cotton with legume cover crop was 7.5g C kg^{-1} and under continuous cotton without cover crop was 3.9 g C kg^{-1} (Reeves, 1997).

Table 2. Estimate of soil organic C sequestration with adoption of conservation tillage compared with conventional tillage in different Major Land Resource Areas in the southeastern United States.†

Major Land Resource Area	Number of observations	Depth	Duration	Soil organic C sequestration Mean	SD	H_0: no change ($p > \|t\|$)
		cm	yr	Mg ha^{-1} yr^{-1}		
Appalachian Ridge and Valley	**4**	**22**	**7.3**	**0.78**	**0.64**	**0.05**
Coastal Plain	**17**	**20**	**10.5**	**0.31**	**0.35**	**0.001**
Eastern Texas‡	**6**	**22**	**13.0**	**0.25**	**0.12**	**0.002**
Mississippi Valley Silty Upland	**6**	**15**	**8.8**	**0.14**	**0.16**	**0.04**
Southern Piedmont	**8**	**18**	**6.3**	**1.12**	**0.78**	**0.002**
Southeastern United States	**41**	**19**	**9.5**	**0.48**	**0.56**	**<0.001**

† Data 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).

‡ Eastern Texas composed of Gulf Coast Prairie, Lower Rio Grande Plain, and Texas Blackland Prairie major land resource areas.

With the introduction of conservation tillage to the experiment in 1995, the benefits of crop rotations and cover crops to cotton productivity and SOC concentration have been enhanced (Mitchell et al., 2002; Siri-Prieto et al., 2002).

Cover crops are often planted during periods when the soil might otherwise be fallow and exposed to decomposition and heavy rains. Cover crops (i) protect the soil from water runoff, wind and water erosion, and nutrient leaching, (ii) suppress weeds, (iii) control pests, and (iv) promote sequestration of SOC. From available data, SOC sequestration with adoption of conservation tillage compared with conventional tillage was greater ($p = 0.04$ from 41 unpaired observations) with than without a cover crop (Table 3). 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.

Reeves and Delaney (2002) compared monoculture cotton with an intensive cropping system that maintained actively growing cash or cover crops about 330 d of the year using sunn hemp (*Crotolaria juncea* L.) and ultra-narrow row cotton (20-cm row spacing) in a rotation with wheat (*Triticum aestivum* L.) and corn. All ultra-narrow row systems exhibited higher net returns than traditional row spacing with highest net return over variable costs obtained using continuous no-tillage ultra-narrow row cotton (\$258 ha^{-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 (\$240 ha^{-1} yr^{-1}). Although short-term economics are important to producers, maintenance or improvements in SOC 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 (Derpsch, 2005), 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% (Derpsch, 2005).

Table 3. Soil organic C under conventional tillage and no tillage sorted by cropping systems without and with cover crops.†

Property	Without cover crop (n = 23)		t test	With cover crop (n = 18)	
	Mean	SD	(Pr > t)	Mean	SD
Soil depth, cm	18	5	0.14	20	6
Duration of comparison, yr	10	5	0.84	8	8
Soil organic C with conventional tillage, Mg ha^{-1}	21.5	8.6	0.17	23.6	5.5
Soil organic C with no tillage, Mg ha^{-1}	24.3	8.9	0.13	27.0	5.6
Difference in soil organic C between tillage systems, Mg ha^{-1}	2.8	2.0	0.21	3.3	2.5
Yearly difference in soil organic C between tillage systems, Mg ha^{-1} yr^{-1}	0.33	0.47	0.04	0.67	0.63
Ratio of soil organic C with no tillage-to-conventional tillage, Mg Mg^{-1}	1.15	0.16	0.37	1.17	0.23

† Data are from multiple references reported in Table 2.

Fertilizers and Manures

Fertilizer or manure application would be expected to increase SOC, 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 United States to assess long-term fertilization effects on SOC 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 0.24 Mg C ha^{-1} yr^{-1} with the application of 108 kg N ha^{-1} yr^{-1}. This calculation assumed a C cost of 1.23 kg C kg^{-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 emission, which has 296 times the global warming potential of CO_2 (Intergovernmental Panel on Climate Change, 1997), net C offset from N fertilization would be maximized at 0.07 Mg C ha^{-1} yr^{-1} with the application of 24 kg N ha^{-1} yr^{-1}. These calculations suggest a positive, but diminishing return of investment with increasing application of N fertilizer, regarding mitigation of GHG emission.

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 United States, 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 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 SOC 2.7 Mg C ha^{-1} in a cotton–corn rotation with cover crops in the Coastal Plain (Terra, 2004). The limited studies conducted on animal manure application to cotton production systems suggest that both yield and SOC sequestration can be increased. More research is urgently needed to investigate the effect of animal manure application on SOC 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.

Pasture-Based Crop Rotation

Soil organic C sequestration under pasture management systems in the southeastern United States can exceed sequestration rates observed under crop management systems. From 12 observations of various pasture establishment studies, SOC sequestration was 1.03± 0.90 Mg C ha^{-1} yr^{-1} during an average of 15 yr of investigation (Franzluebbers, 2005). Rotation of crops with pastures could take advantage of high SOC and promote higher productivity under ideal conditions, because (i) surface soil would be enriched in soil organic matter and organically bound nutrients, (ii) some weed pressures could be reduced, (iii) soil water storage could be enhanced, and (iv) disease and pest pressures could be reduced. Successful crop and pasture rotation systems have been developed with conservation tillage in South America (Diaz-Zorita et al., 2002; Garcia-Prechac et al., 2004). These studies have demonstrated that SOC 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 SOC 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 SOC was found for peanut (*Arachis hypogaea* L.) rotated with 4 yr of bahiagrass (*Paspalum notatum* Fluegge) (5.4 g C kg^{-1}) and peanut rotated with 2 yr of bahiagrass (5.2 g C kg^{-1}) (J. Shaw, unpublished data, 2004). Lowest SOC concentration was found for continuous peanut (3.9 g C kg^{-1}) and peanut–fallow (4.0 g C kg^{-1}). This experiment also showed that irrigation increased SOC concentration by 37%. At the same location, SOC concentration of the surface 5 cm in a long-term cotton–peanut rotation (initially 7.6 g C kg^{-1}) increased to 9.4 g C kg^{-1} following introduction of winter annual pasture [oat (*Avena sativa* L.) or ryegrass (*Lolium multiflorum* Lam.)] for 3 yr (Siri-Prieto, 2004).

Much more research is needed to determine the potential for SOC sequestration and crop productivity under pasture-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 from pasture-based crop rotations could be either bane or blessing, depending on specific circumstances producers face (Marois et al., 2002). Scientifically, however, sod-based crop rotations make a great deal of agronomic and environmental sense.

POLITICS AND PROGRAMS TO FOSTER SOIL ORGANIC CARBON SEQUESTRATION

Although the United States did not ratify the Kyoto Protocol, sufficient political pressure exists to reduce or mitigate GHG emissions. In February 2002, the USDA received specific instructions from President George W. Bush to design incentives for landowners to adopt production practices and land uses that increase C sequestration. The Bush administration has committed to reduce GHG emission intensity 18% (i.e., emission per unit of economic activity) 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 United States places business assets at risk and has stimulated a private market for C trading. Current indications are that a mandatory GHG emission cap would unlikely be legislated in the United States (Young, 2003).

Currently, there are two reasonable scenarios in which farmers in the United States might be additionally compensated for the environmental service of SOC 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 SOC. 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.

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 SOC sequestration. The following two programs are administered by the USDA Natural Resources Conservation Service (2005) 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 are:

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

EQIP offers contracts with a minimum term that ends 1 yr after the implementation of the last scheduled practice and a maximum term of 10 yr. 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 yr.

In fiscal year 2004, the CSP provided funding to 18 watersheds in the United States. About 27 300 farms and ranches were within these watersheds, covering 5.7 Mha. In the southeastern United States, three watersheds were targeted: (i) Hondo River in Texas, (ii) Little River in Georgia, and (iii) Saluda River in South Carolina. The program has been expanded to more watersheds in 2005. An enrolled landowner in one of these watersheds would receive a payment based on computation of expected outcomes from chosen practices. Cotton farmers using conservation tillage could be expected to receive anywhere from no payment to \$20 ha^{-1}, with an average of \$8.30 ha^{-1} from various simulations in the region (Causarano et al., 2005).

Carbon Trading Market

A strategy to capitalize on the emission and sequestration of GHGs 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 SOC 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 SOC sequestration.

Since the marginal cost of sequestering increasingly greater quantities of C rises, the likelihood of purchasing higher-cost credits for SOC 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 > \$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 GHG emission.

The magnitude of uncertainty associated with a possible limit on GHG 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 SOC sequestration will depend on the demand for and competitiveness of C credits and the future roles of aggregators and government programs.

An example of C trading on the Chicago Climate Exchange between farmers and an aggregator has been established (Iowa Farm Bureau, 2005). To be eligible for exchange soil offset, land must be under continuous conservation tillage (no-till, strip-till, or ridge-till) and must not have soybean planted for more than 2 yr within a 4-yr period. Exchange soil offsets were issued at the rate of 0.34 Mg C ha^{-1} yr^{-1} for commitment to conservation tillage and 0.51 Mg C ha^{-1} yr^{-1} for commitment to perennial grass cover. Transfer price of exchange soil offsets would be the sales price as determined by sale through the Chicago Climate Exchange less a 10% service fee. Weighted average price was \$5.54 to \$5.87 Mg^{-1} C in March 2005.

Considering the average SOC sequestration rate of 0.48 Mg C ha^{-1} yr^{-1} for conservation-tillage cotton production systems in the southeastern United States (Table 2) and an average price of a C credit at \$5.70 Mg^{-1} C, a cotton producer in the southeastern United States might expect to receive \$2.74 ha^{-1} yr^{-1}, assuming SOC 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. With current information, a cotton producer could expect to get a lower payment from a C credit market than from land enrolled in the CSP.

The currently low prices of C credits in the United States 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, current trades are expected to mature at \$16 to 20 Mg^{-1} C in 2010 (CO2e, 2005).

CONCLUSIONS

Current and future agricultural management systems could help to mitigate GHG emission by sequestering greater quantities of C in soil organic matter with the adoption of conservation practices. A review of literature in cotton production systems in the southeastern United States indicates that SOC could be sequestered at an average rate of 0.48 Mg C ha^{-1} yr^{-1} with no-tillage management. Available data suggested that SOC sequestration would be twice as high by combining no-tillage management with cover cropping (0.67 Mg C ha^{-1} yr^{-1}) than simply no-tillage management without a cover crop (0.34 Mg C ha^{-1} yr^{-1}). More diverse crop rotations of cotton with high-residue-producing crops such as corn and small grains would lead to greater SOC sequestration. Animal manure application to cotton production systems could also stimulate an increase in SOC 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.

Cotton producers in eligible watersheds could expect to receive an average of \$8.30 ha^{-1}, with payments up to \$20 ha^{-1}, depending on practices employed and soil conditions, if enrolling in the Conservation Security Program. Through open-market trading of C credits, cotton production systems managed with conservation tillage could expect to yield less than \$3 ha^{-1}, although prices would be sensitive to world market developments and adoption of U.S. government polices to cap GHG emissions. Soil organic C sequestration in typical cotton production systems in the southeastern United States would yield about \$10 ha^{-1} using C trading prices projected under the Kyoto Protocol.

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

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