Effectiveness of the soil conditioning index as a carbon management tool in the southeastern USA based on comparison with EPIC

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Abstract: Models are being developed and utilized by scientists and government agencies to quantify the potential for carbon storage in soil. The Environmental Policy Integrated Climate (EPIC) v. 3060 model is a process-based model requiring detailed inputs. The soil conditioning index (SCI) is a simpler tool to predict relative change in soil organic carbon (SOC) using table values for three management components (i.e., organic matter, field operations, and erosion) within the framework of the Revised Universal Soil Loss Equation 2 model. Our objective was to determine whether SOC sequestration from no-tillage cropping systems in the southeastern USA could be simply predicted with SCI compared with detailed simulations using EPIC. Four management systems were evaluated: (1) cotton (*Gossypium hirsutum* L.) with conventional tillage, (2) cotton with no tillage, (3) corn (*Zea mays* L.)–cotton rotation with no tillage, and (4) bermudagrass (*Cynodon dactylon* L.)–corn–cotton rotation with no tillage. All no-tillage systems used wheat (*Triticum aestivum* L.) as a cover crop. Simulated SOC sequestration with EPIC was 0.46 ± 0.06 Mg ha^{-1} yr^{-1} (410 ± 51 lb ac^{-1} yr^{-1}) under the three no-tillage management systems and -0.03 Mg ha^{-1} yr^{-1} (-30 lb ac^{-1} yr^{-1}) under conventional tillage. The SCI also predicted a strong difference in SOC between conventional and no tillage. Differences in SOC sequestration among crop rotations were not readily apparent with EPIC but were with SCI. Predictions of SOC sequestration with SCI were comparable to those with EPIC but not necessarily in a linear manner as previously suggested. The SCI appears to be a valuable method for making reasonable, cost-effective estimates of potential changes in SOC with adoption of conservation management in the southeastern USA, although validations under actual field conditions are still needed.

Key words: conservation tillage—cover cropping—crop rotation—modeling—water-use efficiency

Carbon sequestration in soil has emerged as a technology with significant potential for stabilizing atmospheric concentrations of greenhouse gases at nonthreatening levels (Izaurralde et al. 2006). Estimates of long-term soil organic carbon (SOC) storage in agricultural cropping systems are needed to evaluate the effectiveness of different management systems across a wide range of soil, crop, and climate conditions (Causarano et al. 2006).

The southeastern USA is a warm, humid region conducive to high C fixation in plant biomass but is also known for high rates of decomposition (Franzluebbers 2005). The southeastern USA can be defined as an area from eastern Texas to Virginia and southwards (figure 1). The impact of agricultural management practices on SOC will vary depending on climatic conditions that influence plant and soil processes driving soil organic matter dynamics (Ogle et al. 2005). Comparing regions of North America, the effect of conservation tillage on SOC sequestration was greatest in the central and southeastern USA and lowest in the northeastern USA and eastern Canada (Franzluebbers and Follett 2005). In the southeastern USA, SOC sequestration was most significant with forage management systems, cover cropping, manure application, and conservation tillage (Franzluebbers 2005).

Agronomic and environmental benefits of conservation tillage may be greatly enhanced by diverse crop rotations and cover cropping (Reeves 1994; Lal 2003). In addition, several studies have shown how conservation tillage can improve yield and crop water use efficiency (WUE) and can reduce water runoff and soil erosion (Unger and Vigil 1998; Norwood 1999; Hatfield et al. 2001; Reddy et al. 2004; Truman et al. 2005). Conservation tillage, winter cover cropping, crop rotation, and residue management improve soil quality, which increases the availability of plant nutrients, conserves soil moisture, improves infiltration, and reduces erosion, runoff, and surface crusting.

Sandy soils, such as those typical of the Coastal Plain region, are naturally low in SOC. Coarse-textured soils provide less protection of SOC as residues decompose and exhibit higher decomposition rates than fine-textured soils (Franzluebbers 1999; Krull et al. 2001). Before modern conservation tillage technology was available, increasing SOC was believed to be nearly impossible in sandy Coastal Plain soils. However, on a sandy soil in the South Carolina Coastal Plain, long-term conservation tillage of row crops was shown to be a viable method for increasing SOC (Hunt, et al. 1996). On coarse-textured soil in the Coastal Plain of Alabama, SOC sequestration was 6 to 10 Mg ha^{-1} (2.7 to 4.5 ton ac^{-1}) with high-residue-producing conservation systems and dairy manure application for three years, which was much greater than expected for degraded soils of the southeastern USA (Terra et al. 2005). Under forage management systems on medium-textured soils in Virginia, Conant et al. (2003) found that SOC sequestration averaged 0.41 Mg C ha^{-1} yr^{-1} (366 lb ac^{-1} yr^{-1}). In the Georgia Piedmont, par-

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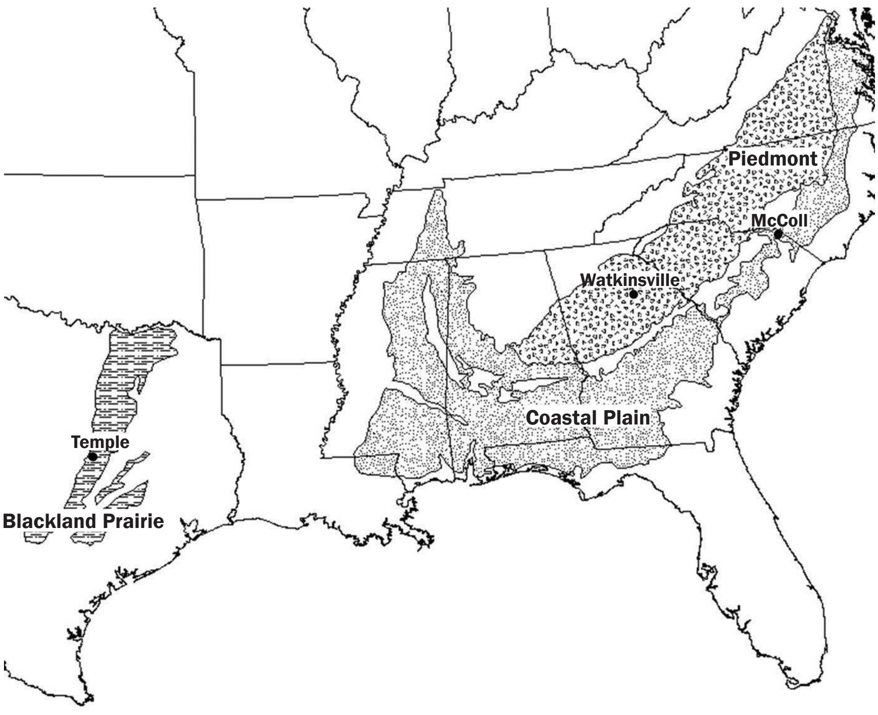
Figure 1
Location of the three sites within the Blackland Prairie, Coastal Plain, and Southern Piedmont major land resource areas in the southeastern USA.



ticulate and biologically active soil C fractions increased in all forage management systems, but they increased more in grazed than in ungrazed systems because of the return of feces to the soil (Franzluebbers and Stuedemann 2003).

The amount of SOC sequestered in a field or region is costly to measure and monitor. Protocols are still being developed, making it difficult to base policies directly on environmental performance (Feng et al. 2004). There are relatively few long-term management studies within the southeastern USA that holistically address SOC sequestration (i.e., measuring plant and soil responses over an extended period of time). Simulation modeling can be an efficient method for estimating management effects on soil properties for a wide range of soil and climatic conditions (Williams et al. 1984). However, the accuracy and sensitivity of models to a variety of environmental and managerial factors needs to be assessed.

The Erosion Productivity-Impact Calculator (renamed the Environmental Policy Integrated Climate, EPIC) model comprehensively simulates important soil, crop, and environmental processes relevant to ecosystem functioning (Williams et al. 1984; Williams 1990; Gassman et al. 2004). EPIC was recently updated to include a C- and N-transformation submodel with concepts and equations derived from the CENTURY model (Izaurralde et al. 2006). The revised EPIC model (v. 3060) was tested against field data from a six-year experiment at five sites in the Great Plains USA and from a 61-year agronomic experiment near Breton, Canada. The model accounted for 91% of the variability in SOC at Breton, but it overestimated SOC at the Great Plains sites when initial SOC was low and underestimated SOC when initial SOC was high (Izaurralde et al. 2006). After optimization of the humus fraction in the passive C pool, the model was able to simulate the observed decline in SOC with continuous conventional tillage and that of restored grassland areas at three locations in central Texas (Gassman et al. 2004). EPIC v. 3060 is process-based and requires extensive expertise, user time, and data requirements unique to specific locations, which can result in high-quality outputs of plant production characteristics and SOC changes with time that are especially useful for scientific investigators. Sufficient long-term model projections of SOC and WUE based on various conservation management systems are currently not available in the southeastern USA.

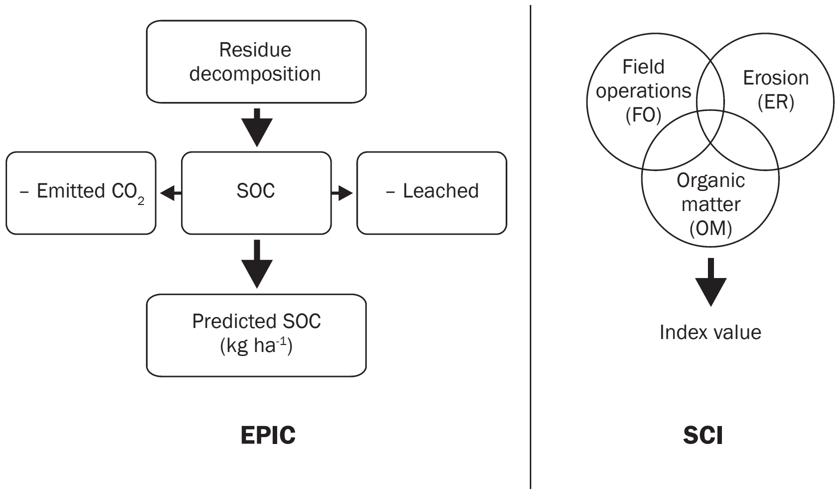
The soil conditioning index was recently incorporated into the Revised Universal Soil Loss Equation (RUSLE2), a model containing both empirical and process-based science to predict erosion from rainfall and runoff (USDA NRCS, 2006). The USDA Natural Resource Conservation Service (NRCS) uses the soil conditioning index (SCI) to predict changes in SOC based on different agricultural management practices. The SCI is used to calculate payments to landowners enrolled in the USDA NRCS Conservation Security Program (Hubbs et al. 2002), which is currently making payments of \$28.65 ha^{-1} yr^{-1} (\$11.60 ac^{-1} yr^{-1}) times a positive SCI value. The SCI is a relatively simple function of three components known to affect SOC: (1) organic material grown on or added to soil, (2) field operations that alter organic material placement in the soil profile and that stimulate organic matter breakdown, and (3) erosion that removes and sorts surface soil organic matter (from sheet, rill, or wind erosion but not from concentrated flow erosion such as ephemeral or gully erosion) (USDA NRCS 2003).

Testing of the SCI has been limited, suggesting that research is greatly needed to document the potential success and deficiency of the model. The SCI is well-suited for its intended use in conservation planning because of its relatively simple, qualitative approach and indexed output (figure 2). The objectives of our study were to simulate long-term SOC, yield, and WUE under conventional and conservation management systems using EPIC v. 3060 in three major land resource areas (MLRAs) of the southeastern USA and to determine if SOC change predicted by EPIC was correlated with the simpler approach of SCI. The management systems represented a gradient of conservation management and crop diversity, which were expected to affect soil disturbance and C input.

Methods and Materials

Simulations were conducted for locations in the Blackland Prairie in eastern Texas, the Southern Piedmont in northern Georgia, and the Coastal Plain in South Carolina (figure 1). Soil properties at the three locations were obtained from the USDA NRCS SSURGO and STATSGO databases (Soil Survey Staff 2007) included with the EPIC model (table 1).

Figure 2
Diagrams comparing the process-based approach of the EPIC soil organic carbon submodel (left) and the index approach of the soil conditioning index (SCI) (right).



Note: SOC = soil organic carbon; FO = field operation; ER = erosion OM = organic material.

The Blackland Prairie site was located on a Houston Black clay (fine, smectitic, thermic Udic Haplusterts) near Temple, Texas, at 31°5' N, 97°35' W, elevation 210 m (689 ft). Grain sorghum (*Sorghum bicolor* [L.] Moench), cotton, corn, small grains, and forage grasses are common in the MLRA. Annual precipitation ranges from 500 to 1,150 mm (30 to 45 in), annual temperature ranges from 17°C to 21°C (63°F to 70°F), and the growing season lasts 230 to 280 days.

The Coastal Plain site was located on a Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults) near McColl, SC at 34°67' N, 79°00' W, elevation 56 m (185 ft). Cotton, tobacco (*Nicotiana tabacum* L.), soybean (*Glycine max* [L.] Merr.), peach (*Prunus persica* [L.] Batsch), hay, wheat, and corn are common in this MLRA. Annual precipitation averages 1219 mm (48 in), annual temperature averages 23°C (74°F), and the growing season is 290 days.

The Southern Piedmont site was located on a Cecil sandy clay loam (fine, kaolinitic, thermic Typic Kanhapludults) near Watkinsville, GA at 33°54' N, 83°24' W, elevation 229 m (751 ft). Cotton, corn, small grains, and forage grasses are common in this region. Annual precipitation averages 1,143 mm (45 in), annual temperature averages 17°C (63°F), and the growing season lasts 200 to 250 days.

EPIC v. 3060 without calibration was used to simulate yield, WUE, and SOC. Baseline data including soil series properties from the NRCS database, crop parameters, location-specific weather data, and management operations were required to run the model. No adjustments to any parameters such as decomposition rates, physical crop characteristics, or a large variety of other

Table 1
Selected initial soil parameters from the SSURGO database used for the 50-year simulations with the EPIC model.

Depth (m)	Bulk density (Mg m^{-3})	Sand (kg kg^{-1})	Silt (kg kg^{-1})	pH	Soil organic C (g kg^{-1})
		Blackland Prairies (Houston black clay)			
0.01 to 0.18	1.3	0.07	0.36	8.0	15
0.18 to 0.48	1.2	0.05	0.39	8.3	13
0.48 to 1.0	1.3	0.06	0.35	8.0	9
1.0 to 1.5	1.4	0.06	0.40	8.3	4
1.5 to 2.0	1.3	0.07	0.42	8.2	3
		Coastal Plain (Norfolk loamy sand)			
0.01 to 0.18	1.6	0.76	0.22	4.9	6
0.18 to 0.48	1.7	0.55	0.25	4.7	2
0.48 to 1.0	1.4	0.56	0.13	4.6	<1
1.0 to 1.5	1.3	0.62	0.12	4.6	1
1.5 to 2.0	1.3	0.41	0.24	4.5	<1
		Southern Piedmont (Cecil sandy clay loam)			
0.01 to 0.18	1.6	0.68	0.20	5.5	4
0.18 to 0.28	1.5	0.55	0.17	5.0	2
0.28 to 1.2	1.4	0.18	0.29	5.0	1
1.2 to 2.0	1.7	0.45	0.26	4.5	<1

variables were made. Initialization of EPIC is usually not important for decadal-long simulations, as the model equilibrates dynamically in the first few years when soil and climatic processes respond to management practices. EPIC estimates initial conditions, such as soil water content, if not provided. For example, we allowed EPIC to compute initial soil water content as a function of field capacity and mean annual precipitation using the equation:

$$FFC = AAP / (AAP + e^{(9.043 - 0.002135 * AAP)})$$

where FFC is fraction of field capacity and AAP is average annual precipitation (mm).

Four management systems in each MLRA were (1) monoculture cotton with conventional tillage (CT), (2) cotton/wheat cover (within a year) under no tillage (NT), (3) corn/wheat cover (four-year)–cotton/wheat cover (four-year) rotation under NT, and (4) bermudagrass (*Cynodon dactylon* L.) pasture (five-year)–corn/wheat cover (five-year)–cotton/wheat cover (five-year) under NT. Management characteristics can be found in table 2. Planting dates were from averages reported in USDA-NASS (1997). Fertilizer application to bermudagrass was based on a recommendation for the region (Dwight Fisher 2006). Climatic inputs were generated using WXGEN in the EPIC model (Williams and Sharpley 1990), based on long-term climatic conditions at weather stations near the three locations (NCDC 2007). The potential heat unit threshold to simulate cotton yield was set at 2,800 in a standard simulation but was allowed to be lower (automatically set by the model) in a companion simulation to evaluate the effect of altered yield on SOC sequestration.

Yearly estimates of SOC (0 to 2 m depth), crop yield, and WUE were simulated by EPIC for a 50-year period. Water-use efficiency (kg mm^{-1}) was calculated as simulated yield (lint for cotton and grain for corn) divided by simulated evapotranspiration during the growing season (generally May to October for cotton and April to August for corn). Simulated estimates of yield and WUE within a MLRA and management system were averaged across years prior to analysis of variance. Simulated SOC estimates were regressed on year in each MLRA and management system to obtain a linear rate of change with time. Yearly estimates of SOC within a MLRA and management system were also fitted to a nonlinear exponential model to obtain total SOC sequestered during 50 years:

$$Y_t = A + B\,(1 - e^{-k * t})$$

where Y is SOC sequestered (Mg ha^{-1}) at time t (yr), A is initial SOC (Mg ha^{-1}), B is potential SOC sequestration (Mg ha^{-1}), and k is the nonlinear rate of SOC sequestration (yr^{-1}).

The resultant single estimates for yield, WUE, and SOC for each MLRA and management system were used as independent estimates in an analysis of variance that included MLRA as a blocking variable (n = 3) and management system as a response variable (n = 4). Significance among means with true replications was declared at $P \leq 0.1$. To test for potential interactions between MLRA and management system, despite not having replication of MLRA estimates, we used consecutive five-year mean slope values of SOC as pseudoreplications within the 50-year evaluation period. Significance among means with pseudoreplications was declared at $P \leq 0.01$.

Using the same management conditions as for EPIC simulations, SCI values were developed for a 50-year period for the four management scenarios and three MLRAs using RUSLE2 (USDA-NRCS, 2006).

The relationship between SOC sequestration predicted by EPIC and SCI was determined with linear regression (all 12 paired estimates) and non-linear regression (excluding the NT bermudagrass-corn-cotton rotation, which deviated the most from the linear regression). General linear models were analyzed with SAS for Windows 9.1. Regressions were performed with SigmaPlot for Windows 8.02.

Results and Discussion

EPIC Simulations of Soil Organic Carbon. Organic C content within the surface 2 m of soil generally remained unchanged with time under CT and increased with time in all NT management systems (figure 3). Averaged across MLRAs, the rate of simulated SOC sequestration (Mg ha^{-1} yr^{-1}) was greater under NT management systems than under CT (table 3). The total quantity of SOC sequestered during the 50 years of simulation was also greater under NT management systems (27.0 ± 7.7 Mg ha^{-1}) than under CT (-1.5 Mg ha^{-1}). There was no statistical difference in the simulated rate of SOC sequestration or total amount of SOC sequestered among the three NT management systems.

The absolute amount of C in the soil profile was different among the three MLRAs, but the relative change in SOC due to management did not differ among MLRAs (figure 3). The main effect of greater SOC sequestration rates with NT systems than with CT (table 3) did not differ significantly among MLRAs (P = 0.28). The interaction test used five-year rates of SOC sequestration as observations. Mean ± standard deviation among the five-year rates was 0.00 ± 0.22 Mg ha^{-1} yr^{-1} (-1 ± 151 lb ac^{-1} yr^{-1}) under CT cotton, 0.51 ± 0.65 Mg ha^{-1} yr^{-1} (457 ± 500 lb ac^{-1} yr^{-1}) under NT cotton/wheat cover, 0.52 ± 0.69 Mg ha^{-1} yr^{-1} (467 ± 547 lb ac^{-1} yr^{-1}) under NT corn/wheat cover-cotton/wheat cover, and 0.59 ± 2.43 Mg ha^{-1} yr^{-1} (527 ± 1961 lb ac^{-1} yr^{-1}) under NT bermudagrass-corn/wheat cover-cotton/wheat cover. A relatively large variation in the SOC sequestration rate was observed in all four management systems, likely due to weather variations that may have affected crop production and soil organic matter decomposition. Particularly large variation was observed in the bermudagrass-corn-cotton rotation. The mean and standard deviation of SOC sequestration rate under NT cotton and NT corn/wheat cover-cotton/wheat cover were similar to those reported for 96 observations of NT versus CT in 10 ± five-year studies across the southeastern USA region (0.42 ± 0.46 Mg ha^{-1} yr^{-1}; Franzluebbers, 2005). Therefore, simulation of SOC sequestration with EPIC was generally consistent with field-based data. Whether management systems could maintain these high SOC sequestration rates for a 50-year period rather than the 10 ± 5 year periods of actual field measurements is still questionable and needs to be answered with long-term field experimentation.

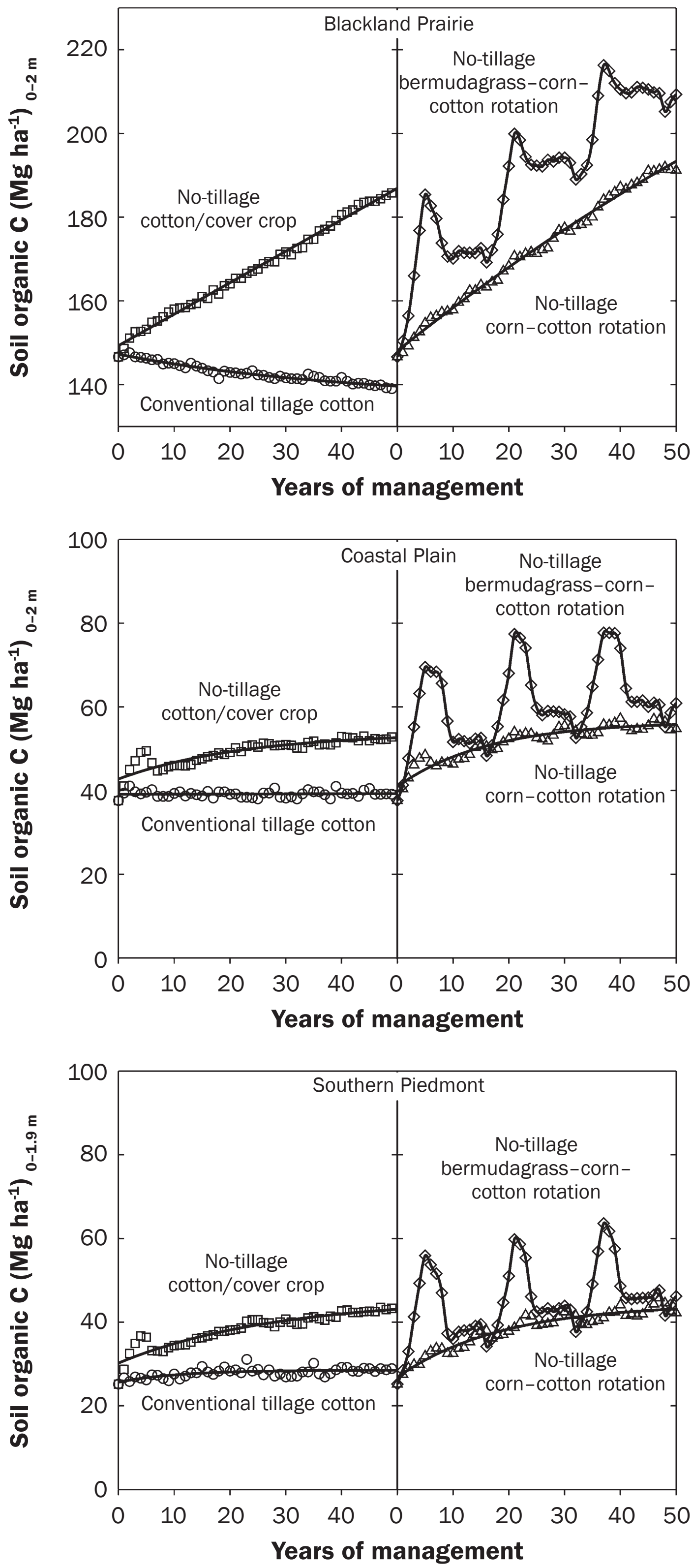
EPIC simulated very large SOC sequestration in the bermudagrass phase of the bermudagrass-corn-cotton rotation and large declines immediately thereafter (figure 3). The large decline in SOC following termination of pasture was unrealistic (Garcia-Prechac et al. 2004), since crops were managed under no tillage. Although forage management systems have shown potential for high SOC sequestration in the southeastern USA (1.03 ± 0.90 Mg ha^{-1} yr^{-1}; Franzluebbers 2005), the simulated rate of SOC sequestration dur-

Table 2
Management characteristics for 50-year simulations by the EPIC model in each of the three major land resource areas and four management systems.

	Date of operation		
Management operation	**Blackland Prairie**	**Coastal Plain**	**Southern Piedmont**
Monoculture cotton with conventional tillage			
Fertilizer/plant cotton (150 kg N, 37 P ha^{-1})	May 25	May 5	Apr. 25
Cultivate	Jun. 15	Jun. 10	Jun. 10
Harvest cotton	Nov. 15	Oct. 25	Oct. 30
Offset disk	Nov. 15	Nov. 5	Nov. 5
Tandem disk	Nov. 30	Nov. 30	Nov. 30
Rotation repeated yearly			
Cotton/wheat cover crop with no tillage (NT)			
Cut/bale wheat	May 20	May 1	Apr. 20
Fertilize/plant cotton (150 kg N, 37 P ha^{-1})	May 25	May 5	Apr. 25
Harvest cotton	Oct. 25	Oct. 30	Oct. 30
Fertilize/plant wheat (56 kg N ha^{-1})	Oct. 30	Oct. 30	Nov. 5
Rotation repeated yearly			
Corn/wheat cover (4-year)–cotton/wheat cover (4-year) with NT			
Years 1–4: Cut/bale wheat	Apr. 25	Apr. 10	Mar. 25
Fertilizer/plant corn (168 kg N, 37 P ha^{-1})	Apr. 30	Apr. 15	Apr. 1
Harvest corn	Sep. 5	Sep. 1	Aug. 5
Fertilizer/plant wheat (56 kg N ha^{-1})	Sep. 10	Sep. 10	Oct. 5
Years 5–8: Cut/bale wheat	Apr. 15	May 1	Mar. 25
Fertilize/plant cotton (150 kg N, 25 P ha^{-1})	May 25	May 5	Apr. 25
Harvest cotton	Nov. 15	Oct. 25	Oct. 30
Fertilize/plant wheat (56 kg N ha^{-1})	Nov. 20	Oct. 30	Nov. 5
Rotation repeated every 8 years			
Bermudagrass (5-year)–corn/wheat cover (5-year-cotton/wheat cover (5-year) with NT			
Year 1: Fertilize/plant bermudagrass (80 kg N, 37 P ha^{-1})	Mar. 15	Mar. 15	Mar. 15
Cut bermudagrass	Jun. 15	Jun. 15	Jun. 15
Fertilize bermudagras (50 kg N ha^{-1})	Jul. 15	Jul. 15	Jul. 15
Cut bermudagrass	Aug. 15	Aug. 15	Aug. 15
Year 2: Fertilize bermudagrass (80 kg N ha^{-1})	Mar. 15	Mar. 15	Mar 15
Cut/bale bermudagrass	Apr. 30	Apr. 30	Apr. 30
Fertilize bermudagrass (50 kg N ha^{-1})	May 1	May 1	May 1
Cut/bale bermudagrass	Jun. 15	Jun. 15	Jun. 15
Fertilize bermudagrass (50 kg N ha^{-1})	Jun. 20	Jun. 20	Jun. 20
Cut/bale bermudagrass	Aug. 1	Aug. 1	Aug. 1
Fertilize bermudagrass (50 kg N ha^{-1})	Aug. 15	Aug. 15	Aug. 15
Years 3–5: Fertilize bermudagrass (80 kg N ha^{-1})	Mar. 15	Mar. 15	Mar. 15
Initiate grazing of bermudagrass	Apr. 15	Apr. 15	Apr. 15
Fertilize bermudagrass (80 kg N ha^{-1})	Jun. 15	Jun. 15	Jun. 15
Fertilize bermudagrass (50 kg N ha^{-1})	Aug. 15	Aug. 15	Aug. 15
End grazing of bermudagrass	Sep. 15	Sep. 15	Sep. 15
Years 6–10: Culture of corn with NT as above			
Years 11–15: Culture of cotton/wheat with NT as above			

Note: Rotation repeated every 15 years.

Figure 3
Simulated soil organic carbon during 50 years by the EPIC model in three major land resource areas as affected by four management systems.



ing the bermudagrass phase of 6.06 ± 0.94 Mg ha^{-1} yr^{-1} (2.7 ± 0.4 ton ac^{-1} yr^{-1}) was larger than expected and was not justified by experimental evidence. Therefore, simulation of SOC under forage management systems should be re-evaluated in EPIC v. 3060 to produce more accurate predictions. The SOC module of EPIC v. 3060 was tested against data collected in various locations and management conditions (Gassman et al. 2004; Izaurralde et al. 2006), but most of these conditions were under cropping systems. Calibration of the model appears to be necessary for predicting SOC sequestration in long-term forage management systems and for locations other than the few already tested. Calibration could provide more accurate prediction of variables, such as biomass production, that would influence the amount of SOC sequestered. The calibration process could also identify sensitive parameters, such as residue decomposition rates, that influence SOC accumulation with time. Parameter adjustments would then have implications for transfer of results across a region (Abrahamson et al. 2005).

Efforts are currently underway to test EPIC v. 3060 as a decision-making tool for C management based on remotely sensed residue management and tillage practices in the midwestern USA (NASA 2005). A similar effort would be useful in portions of the southeastern USA to verify that EPIC could accurately simulate long-term changes in SOC throughout the entire southeastern USA.

Soil Conditioning Index Prediction of Soil Organic Carbon Change and Relationship to EPIC Predictions. The SCI predicted that SOC would decline with time under CT and increase with time under all three NT management systems (table 3). The SCI also suggested that including five years of pasture in the cropping system would lead to greater SOC than simpler NT crop rotations (P = 0.10). These results were qualitatively consistent with the predictions from EPIC, although EPIC simulation of SOC sequestration was not statistically different between NT rotation systems.

From the four management systems on three MLRAs, SCI was linearly related to SOC sequestration simulated by EPIC (figure 4). The greatest deviation from this relationship was in the bermudagrass-corn/wheat cover-cotton/wheat cover system. Excluding this management system, the best fit between

Table 3

Estimates of soil organic carbon (SOC) sequestration (0 to 2 m depth) during 50 years of simulation by the EPIC model and the SCI, averaged across three major land resource areas (i.e., Blackland Prairies, Coastal Plain, and Southern Piedmont).

	EPIC		SCI
Management system	Linear rate of SOC sequestration ($Mg\ ha^{-1}\ yr^{-1}$)	Total quantity of SOC sequestration ($Mg\ ha^{-1}$)	Unit-less relative change
(1) CT cotton	–0.03	–1.5	–1.07
(2) NT cotton/wheat cover	0.39	20.1	0.38
(3) NT corn/wheat cover–cotton/wheat cover	0.49	25.5	0.50
(4) NT bermudagrass–corn/wheat cover–cotton/wheat cover	0.50	35.3	0.80
Analysis of variance		**Pr > F**	
CT vs. NT systems (1 vs. 2-3-4)	0.03	0.008	<0.001
NT ungrazed vs. grazed (2-3 vs. 4)	0.77	0.16	0.10
NT monoculture vs. rotation (2 vs. 3)	0.68	0.57	0.58

EPIC and SCI was an exponential growth function that suggested SOC sequestration was insensitive to SCI ≤ 0, but increased dramatically with values > 0. Hubbs et al. (2002) presented linear relationships between the percent C change in soil and SCI. Although the simulation results reported here were in general agreement with the relationships in Hubbs et al. (2002), there is a need for further evaluation of SCI since both linear and non-linear relationships with SOC sequestration appear to be possible, reflecting unexplained sources of variation. An even greater need is to validate SCI against actual field data of SOC sequestration under a wide range of agricultural systems with long-term management. The relationships reported in Figure 4 should not be considered quantitative or be used as a predictive tool, since SOC sequestration estimates were obtained only with EPIC v. 3060 and not actual field data.

EPIC Simulations of Crop Yield and Water-Use Efficiency (WUE). Cotton lint yield was greater under CT than under NT management systems when averaged across MLRAs (table 4). There were no differences in simulated lint yield among the three NT management systems. Cotton lint WUE was not different among any of the treatments, averaging 2.4 kg mm^{-1} (134 lb in^{-1}) (table 4). No tillage was able to reduce evaporation from soil compared with CT, resulting in similar WUE, despite a difference in yield. Simulations of cotton lint yield were relatively high (mean of 1.41 Mg ha^{-1} under CT and 1.24 Mg ha^{-1} under NT systems) compared with actual field observations of 0.98 ± 0.30 Mg ha^{-1} (875 ± 268 lb ac^{-1}) under CT and 1.05 ± 0.22 (938 ± 196 lb ac^{-1}) under NT (Johnson et al. 2001; Endale et al. 2002; Busscher and Bauer 2003; Schomberg et al. 2003). However, relative differences among treatments were expected to occur to a similar extent, irrespective of absolute values. Calibration of EPIC to specific growing conditions in these environments appears to be necessary to improve yield estimates.

Simulation of 12% ± 6% lower cotton lint yield with NT management systems compared with CT was different than most reported field observations. In a review of tillage impacts on soil and crop responses in the southeastern USA, cotton lint yield across 18 pairs of observations (CT vs NT) averaged 1.1 Mg ha^{-1} (982 lb ac^{-1}) and was not different between tillage systems (Franzluebbers 2005). Seed cotton yield across nine pairs of observations was 2.59 Mg ha^{-1} (2,312 lb ac^{-1}) under CT and 2.69 Mg ha^{-1} (2,402 lb

Table 4

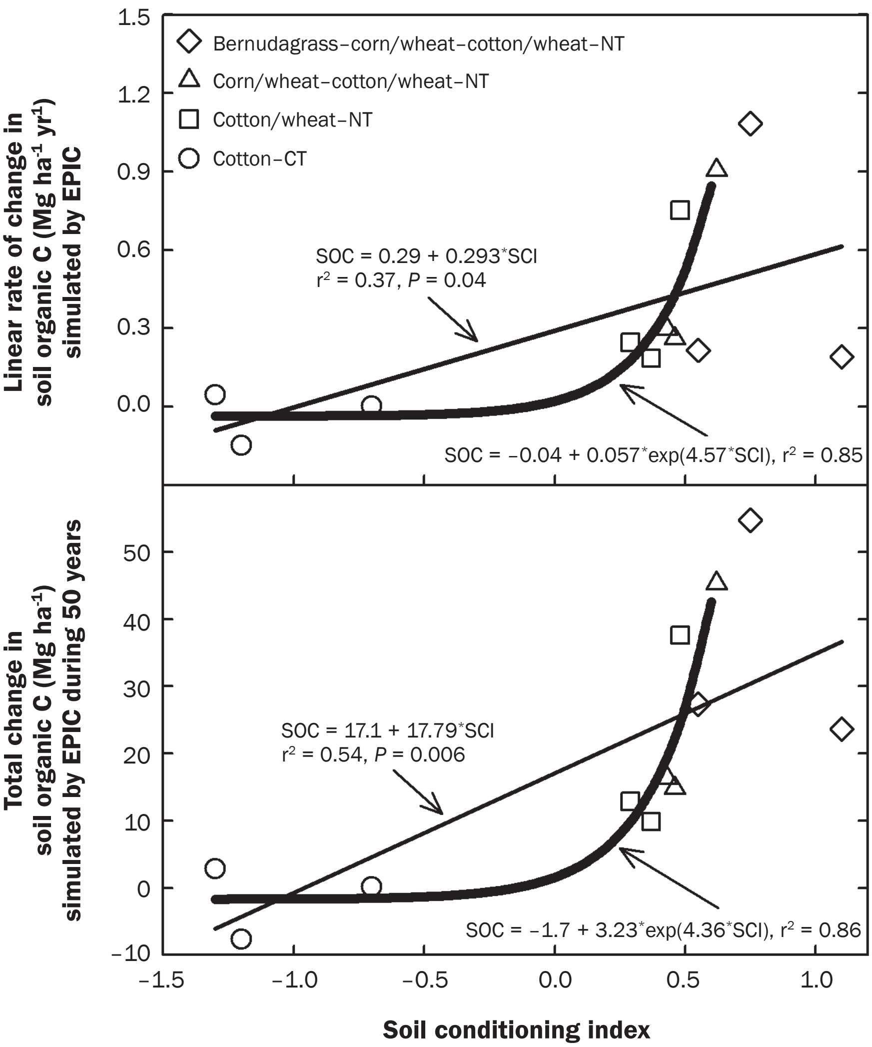
Mean cotton lint yield, corn grain yield, and water-use efficiencies averaged across three major land resource areas (i.e., Blackland Prairie, Coastal Plain, and Southern Piedmont) during 50 years of simulation by the EPIC model.

	Yield ($Mg\ ha^{-1}$)		Water-use efficiency ($kg\ mm^{-1}$)	
Management system	Cotton lint	Corn grain	Cotton lint	Corn grain
(1) CT cotton	1.41	NA	2.45	NA
(2) NT cotton/wheat cover	1.15	NA	2.29	NA
(3) NT corn/wheat cover–cotton/wheat cover	1.32	7.53	2.41	18.5
(4) NT bermudagrass–corn/wheat cover–cotton/wheat cover	1.24	6.90	2.34	17.0
Analysis of variance		**Pr > F**		
CT vs. NT systems (1 vs. 2-3-4)	0.06	NA	0.22	NA
NT ungrazed vs. grazed (2-3 vs. 4)	0.96	0.04	0.90	0.24
NT monoculture vs. rotation (2 vs. 3)	0.11	NA	0.21	NA

Note: NA = not applicable.

Figure 4

Soil organic carbon sequestration simulated by the EPIC model in the surface 2 m of soil on a yearly basis (top) and throughout a 50-year period (bottom) in relationship with the SCI.



Notes: Linear relationships were developed with all 12 observations (4 management systems x 3 major land resource areas). Exponential growth curves were fitted to data, excluding the bermudagrass–corn/wheat cover–cotton/wheat cover system under no tillage (NT). CT = conventional tillage.

ac^{-1}) under NT. Terra et al. (2005) reported 17 ± 9% greater seed cotton yield under NT than under CT. The negative effect of NT management on simulated cotton lint yield during 50 years of management supports the need for calibration of EPIC v. 3060 to specific conditions at a site to account for differences among management systems. Cotton lint WUE from a silt loam soil in Alabama was 3.0 ± 1.4 kg mm^{-1} (167 ± 78 lb in^{-1}) under both CT and NT, when using precipitation from May to September in calculations (Reddy et al. 2004). On a loamy sand in South Carolina, cotton lint WUE was 1.3 ± 0.3 kg mm^{-1} (73 ± 17 lb in^{-1}) under both CT and NT (Busscher and Bauer 2003). On a silt loam in Mississippi, cotton lint WUE was 2.5 ± 0.8 kg mm^{-1} (139 ± 45 lb in^{-1}) under CT and 2.2 ± 0.6 kg mm^{-1} (123 ± 33 lb in^{-1}) under NT (Pettigrew and Jones 2001). On a sandy loam soil in Alabama, seed cotton WUE was 5.1 ± 2.0 kg mm^{-1} (285 ± 112 lb in^{-1}) under CT and 5.3 ± 2.0 kg mm^{-1} (296 ± 112 lb in^{-1}) under strip tillage (Gordon et al. 1990). On a silt loam in Mississippi, seed cotton WUE was 4.2 ± 1.4 kg mm^{-1} (234 ± 78 lb in^{-1}) under CT and 4.9 ± 1.9 kg mm^{-1} (273 ± 106 lb in^{-1}) under NT (Triplett et al. 1996). The measured effect of tillage system on WUE in cotton has generally been relatively small and inconsistent, and therefore, simulations of similar cotton WUE efficiency between CT and NT systems during 50 years were reasonable compared with available field data.

Simulated corn grain yield was 9% greater under the NT corn/cotton rotation than under the NT pasture-crop rotation system (table 4). Simulated corn grain yield production was well within observed production levels of 6.7 ± 1.8 Mg ha^{-1} (107 ± 29 bu ac^{-1}) under CT and 7.6 ± 1.7 Mg ha^{-1} (121 ± 27 bu ac^{-1}) under NT on soils in the same three MLRAs (Hargrove 1985; Karlen et al. 1989; Wagger and Denton 1992; Torbert et al. 2001; Terra et al. 2005). Water-use efficiency of corn was not different between the two rotations, averaging 17.6 ± 1.4 kg grain mm^{-1} (18 ± 1 bu in^{-1}) precipitation. On a clay soil in Texas, corn grain WUE was 8.8 ± 4.6 kg mm^{-1} (9 ± 5 bu in^{-1}) under CT and 11.5 ± 3.5 kg mm^{-1} (11 ± 3 bu in^{-1}) under NT (Torbert et al. 2001). Under dryland conditions in Kansas, corn grain WUE was 10.0 ± 4.9 kg mm^{-1} (10 ± 5 bu in^{-1}) under CT and 12.8 ± 4.3 kg mm^{-1} (13 ± 4 bu in^{-1}) under NT (Norwood 1999). On a fine sandy loam in Alabama, corn grain WUE was 20.1 ± 6.3 kg mm^{-1} (20 ± 6 bu in^{-1}) under continuous corn and 21.3 ± 6.2 kg mm^{-1} (21 ± 6 bu in^{-1}) under wheat/soybean/corn (Edwards et al. 1988).

Effect of Altered Crop Yield Prediction on Soil Organic C. By lowering the threshold heat unit level from 2800 to 2000, cotton lint yield increased 36% from a mean of 1.28 Mg ha^{-1} to 1.75 Mg ha^{-1} (1,143 to 1,562 lb ac^{-1}), averaged across treatments (data not shown). However, SOC sequestration declined from a mean of 0.34 Mg ha^{-1} yr^{-1} to 0.28 Mg ha^{-1} yr^{-1} (304 to 250 lb ac^{-1} yr^{-1}). Although conversion of crop-derived C into SOC cannot be treated as a direct function of crop yield, the small decline in SOC sequestration with a relatively large increase in crop yield suggests that simulated SOC sequestration values may be less variable across a range of environments than crop yield.

Summary and Conclusions

Simulations with the uncalibrated EPIC v. 3060 strongly suggested that no-tillage management of cropland in the southeastern USA would lead to significant sequestration of soil organic C compared with conventional-tillage management. Increasing crop rotation diversity did not significantly alter simulated soil organic C sequestration and cotton lint water-use efficiency. The SCI also indicated that soil organic C sequestration would be greater with no-tillage management than with conventional-tillage management, but in addition suggested greater soil organic C sequestration with a more diverse crop rotation system than with continuous cotton under no tillage. With the limited number of simulations (12), the SCI was comparable to EPIC-simulated soil organic C sequestration during 50 years. Relationships suggested that soil organic C sequestration would be highly significant with relatively small changes in positive values of SCI. Long-term changes in soil organic C appeared to be reasonably predicted with both EPIC v. 3060 and SCI. Discrepancies in cotton lint yield between model-simulated (EPIC v. 3060) and empirical data with regards to conventional and conservation tillage suggest that calibration is needed for detailed, process-based scientific investigation in the southeastern USA. The simplicity and cost-effectiveness of SCI should be of great importance to land managers and policy makers for making decisions to improve soil quality for future use, but there is still an urgent need for long-term, field-based data to improve both EPIC and SCI as prediction tools.

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