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Soil quality indices based on long-term conservation cropping systems management

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Abstract

The Soil Management Assessment Framework (SMAF) may provide insight into how conservation practices affect soil quality (SQ) regionally. Therefore, we aimed to quantify SQ in a long-term (15-yr) crop rotation and bio-covers experiment under no-tillage using SMAF. Main effects were cropping rotations of soybean [*Glycine max* (L.) Merr.], corn (*Zea mays* L.), and cotton (*Gossypium hirsutum* L.). Split-block bio-cover treatments consisted of winter wheat (*Triticum aestivum* L.), Austrian winter pea (*Pisum sativum* L. *sativum* var. *arvense*), hairy vetch (*Vicia villosa* Roth), poultry litter, and fallow (control). Seven SQ indicators—soil pH, total organic carbon (TOC), bulk density (BD), soil extractable P and K, electrical conductivity (EC), and sodium adsorption ration (SAR)—were scored using SMAF algorithms, and investigated individually and as an overall soil quality index (SQI). Simple linear regressions were performed between SQI and crop yields. Differences ($p < .05$) in SQI within rotations varied when analyzed across and by depth. Overall, cotton–corn and/or continuous corn had greater SQI than soybean-based rotations. Poultry litter had the greatest TOC, pH, K, and BD scores at the 0- to 15-cm soil depth, and the lowest SQI. Reductions in SQI within bio-covers were linked to P scores. A positive relationship was found between SQI and cotton yield at the 15- to 30-cm soil depth ($R^2 = .48$; $p < .05$). Investigating SMAF scores individually and separately per depth addresses the effects of long-term conservation practices on SQ. Overall, SMAF can be used to develop best management practices and nutrient management strategies.

Abbreviations: BD, bulk density; EC, electrical conductivity; LRR, land resource region; MLRA, major land resource area; MTREC, Middle Tennessee Research Education Center; RECM, Research and Education Center at Milan; SAR, sodium adsorption ratio; SMAF, Soil Management Assessment Framework; SOC, soil organic carbon; SOM, soil organic matter; SQ, soil quality; SQI, soil quality index; TOC, total organic carbon.

1 | INTRODUCTION

The need for increased food production worldwide and the depletion of soil as a finite natural resource has led to growing concerns of sustainable soil systems management. Consequently, conservation agricultural systems have received considerable attention, as they may increase crop productivity with minimum soil degradation compared to conventional tillage systems (Pittelkow et al., 2015; Triplett & Dick, 2008). When evaluated long-term, conservation systems have demonstrated improvements for soil structure, reduced soil erosion, and increased soil organic carbon (SOC) sequestration (Ashworth, Allen, Wight, Saxton, & Tyler, 2014; Chivenge, Murwira, Giller, Mapfumo, & Six, 2007; Lal & Kimble, 1997) and soil fertility (Ashworth, Allen, DeBruyn, Owens, & Sams, 2018; Peigné, Vian, Payet, & Saby, 2018), thus leading to an overall improvement of soil resiliency and quality (Lal, 2015). However, research is still needed to assess the impact of animal manure, cover crops, and cropping rotations on soil quality (SQ).

Soil quality can be conceptualized as a three-legged stool with the function and balance of which requires an integration of three major components—sustained biological, physical, and chemical properties for continued plant and animal health. The concept attempts to balance multiple soil uses with goals for environmental quality and long-term agricultural productivity. Soil quality is defined as "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran & Zeiss, 2000; Karlen et al., 1997). However, concepts of SQ and health are generally deemed inadequate and oversimplified. Moreover, selecting meaningful indicators of SQ that are sensitive to management-induced changes, reflect management goals, and integrate soil properties and processes is an on-going challenge (Karlen et al., 2006). This indicates that research is still needed to improve our understanding of the response of indicators to variations in long-term management.

Crop rotations and cover crops are thought to play a decisive role in SQ. Crop rotations that include species with larger C/N ratios such as corn (*Zea mays* L.) may present greater SOC levels compared with soybean [*Glycine max* (L.) Merr.], due to the amount of residue produced and the reduced residue mineralization in soils (Kaboneka, Sabbe, & Mauromoustakos, 1997; Gentry, Snapp, Price, & Gentry, 2013). Legume cover crops such as hairy vetch (*Vicia villosa* Roth) and Austrian winter pea (*Pisum sativum* L. *sativum* var. *arvense*) are reported to build up soil N due to their low compositional C/N ratio, thus reducing the need for N fertilizer and increasing crop yields (Doran & Smith, 1991; Drinkwater, Wagoner, & Sarrantonio, 1998; Liebman et al., 2018). Grass cover crops such as winter wheat (*Triticum aestivum* L.) are more effective at increasing SOC levels compared with legumes because of their greater belowground biomass and reduced residue decomposition rates (Abdalla et al., 2019; Jarecki & Lal, 2003; Sainju & Singh, 1997). Therefore, crop rotations including the above-mentioned cover crops may enhance SOC sequestration and nutrient availability and potentially improve SQ and crop productivity.

Core Ideas

- Cotton–corn and/or continuous corn had greater soil quality index than soybean-based rotations.
- Overall soil quality differences between bio-covers were greatly affected by changes in P scores.
- Poultry litter applications may reduce soil quality at the soil surface.
- Individual scores provided insight on how soil indicators affect overall soil quality.
- Soil Management Assessment Framework scores addressed the effects of long-term conservation practices on soil quality.

The effects of poultry litter application on SQ in long-term cropping systems need to be better understood. Poultry litter, a mixture of poultry manure and bedding material, is considered a valuable fertilizer due to its content of available N and P. Poultry litter can increase soil fertility and organic matter content (Ashworth et al., 2014) and soil biodiversity (Ashworth et al., 2018) in long-term no-tillage cropping systems. However, continuous application of poultry litter may increase labile N and P levels in soils, favoring nitrate leaching and P runoff (Huang et al., 2016; Sauer et al., 2000), with potential eutrophication of water bodies. Using proper agronomic rates of N and P and correct timing and placement of litter may mitigate runoff and groundwater contamination and minimize deleterious soil and environmental quality impacts.

The Soil Management Assessment Framework (SMAF) developed by Andrews, Karlen, and Cambardella (2004) has emerged as one of the main tools to assess SQ within distinctive soil types and cropping systems. It is a quantitative evaluation method that focuses on dynamic SQ properties, in contrast to the inherent SQ determined by soil forming factors. Therefore, it can be applied to evaluate soil responses to certain management systems over time or to compare different management practices (Wienhold, Andrews, & Karlen, 2005). Conducting an assessment using SMAF requires a three-step process, which includes (a) indicator selection (physical, chemical, and biological), (b) indicator interpretation (scoring curves), and (c) soil quality index (SQI) integration (overall SQI) (Karlen, Andrews, Wienhold, & Zobeck, 2008; Wienhold, Karlen, Andrews, & Stott, 2009). Assessment values are generally expressed as a fraction or percentage of full performance for soil functions, such as crop productivity, nutrient cycling, or environmental protection. Indices may assist land managers in decision-making processes with respect to land use or work as a guide toward specific management goals.

Since its public release in 2004, SMAF has been successfully applied to investigate the impacts of various cropping systems across distinctive soil types and management operations (Cherubin et al., 2016; Stott, Cambardella, Tomer, Karlen, & Wolf, 2011; Wienhold, 2005; Zobeck, Halvorson, Wienhold, Acosta-Martinez, & Karlen, 2008). However, there are only a few studies assessing the effects of long-term conservation cropping systems on soil quality. Mbuthia et al. (2015) assessed the impact of long-term tillage, cover crops, and N fertilization rates on soil microbial community structure, activity, and SQ using SMAF. They demonstrated that long-term no-till and the use of cover crops under continuous cotton (*Gossypium hirsutum* L.) resulted in significant shifts in microbial community structure and activity; enhanced C, N, and P cycling; SQ; and crop yields compared with those under conventional tillage practices. Similarly, Veum et al. (2015) found that diversified no-till rotations with cover crops obtained the highest SMAF scores among annual cropping systems, and that the inclusion of cover crops in the diversified no-till system led to increased soil microbial diversity. The present study aims to quantify SQ in a long-term (15 yr) cover crop, crop rotations, and poultry litter experiment under no-tillage by using SMAF.

2 | MATERIALS AND METHODS

2.1 | Site description and experimental design

Field studies were conducted to assess SQ at two sites with existing long-term, no-tillage cropping systems trials. The first site was located at the University of Tennessee, Middle Tennessee Research and Education Center (MTREC; Spring Hill, TN; 36.02° N, –85.13° W) in Natural Resources Conservation Service (NRCS), Major Land Resource Area (MLRA) 123, referred to as the Nashville Basin in the Land Resource Region (LRR) "N." This area is typical of the karst topography region of middle Tennessee, northern Alabama, central and western Kentucky, and southern Indiana. Soils at this site are classified as a Maury silt loam (fine, mixed, active, mesic Typic Paleudalf). The MTREC has a mean annual temperature of 14.2 °C and 114 cm of precipitation. Prior to plot establishment, this site was under a 2-yr corn–soybean rotation, with half the field being under corn and half soybean. The site received annual additions of dairy manure for 15 yr prior to initiation of the experiment.

The second site was located at the Research and Education Center at Milan (RECM; Milan, TN; 35.54° N, –88.44° W) in MLRA 134 (Southern Mississippi Valley Loess) in the Eastern Gulf Coastal Plain LRR "P." This region covers most of western Tennessee, western Alabama, a major portion of Mississippi, eastern Louisiana, and a small section of western Kentucky. Soils at the RECM are classified as a Loring B2 series (fine-silty, mixed, active, thermic Oxyaquic Fragiudalf), with a mean annual precipitation and temperature being 107 cm and 14.8 °C, respectively. Prior to experimentation this site was planted to corn in 2001, soybean in 2000, and cotton in 1999. During the winter season, wheat was planted for grain, although the year prior to experimentation the site was left fallow.

At both locations, treatments were laid out as a split-block (strip-plot) design, with three replications at Milan and four at the MTREC site. Each location was under long-term no-tillage, where the main crops and cover crops were planted directly into the residue of the previous crop. Whole-block treatments consisted of crop rotations (see Table 1 for whole-plot rotations), with strip-block treatments composed of four bio-covers (green manures and crop residues). At RECM, five different cropping rotations of corn, cotton, and soybean were repeated in 4-yr cycles (i.e., Phases I, II, III, and IV; Table 1) beginning in 2002 and continuing through 2017. Bio-covers of wheat, hairy vetch, Austrian winter pea, poultry litter, and a fallow (winter weeds) control were repeated annually. The same experiment was performed at MTREC without

TABLE 1 Cropping rotations at the Research Education Center, Milan, TN, and Middle Tennessee Research Education Center, Spring Hill, TN, from 2002 (Yr-0) to 2017 (Yr-15)

	Year[a]			
Middle Tennessee Research and Education Center (MTREC)				
	2002	2003	2004	2005
	2006	2007	2008	2009
	2010	2011	2012	2013
	2014	2015	2016	2017
Rotation				
Continuous Cr	corn (Cr)	corn	corn	corn
Cr-Sy	corn	soybean (Sy)	corn	soybean
Continuous Sy	soybean	soybean	soybean	soybean
Research and Education Center (RECM)				
	2002	2003	2004	2005
	2006	2007	2008	2009
	2010	2011	2012	2013
	2014	2015	2016	2017
Rotation				
Continuous Ct	cotton (Ct)	cotton	cotton	cotton
Ct-Cr	cotton	corn	cotton	corn
Continuous Cr	corn	corn	corn	corn
Cr-Cy	corn	soybean	corn	soybean
Continuous Sy	soybean	soybean	soybean	soybean

Note. Continuous Ct, continuous cotton; Ct-Cr, cotton–corn–cotton–corn; Continuous Cr, continuous corn; Cr-Sy, corn–soybean–corn–soybean; Continuous Sy, continuous soybean.

[a]2002–2005, Phase I; 2006–2009, Phase II; 2010–2013, Phase III; 2014–2017, Phase IV.

cotton. This created 30 and 18 unique crop rotation × bio-cover combinations for RECM and MTREC, respectively (Table 1).

Main plots were 6.1 × 12.3 and 4.6 × 12.3 m at RECM and MTREC, respectively. Row crops were planted perpendicular to split plots (bio-covers). Specific details on planting methods, cultivars, and row spacing can be found in Ashworth et al. (2014). Briefly, corn was planted between 12 April and 9 May, soybean was planted between 29 April and 30 May, and cotton was planted between 7 and 12 May. Glyphosate-resistant cultivars were planted during Phases I and II and glufosinate-tolerant cultivars in subsequent phases to minimize development of glyphosate-resistant weed populations. Cover crops were planted approximately mid-October through mid-November during the previous cropping year.

Corn received 128.5 kg N ha^{-1} in the form of urea (CH_4N_2O), whereas cotton received 33.4 kg N ha^{-1} as sidedress applications in May and June each year. Muriate of potash (KCl) was applied to all plots in April at a rate of 112 kg ha^{-1} (K_2O rate). Poultry litter plots received the equivalent of 66.7 kg N (total) ha^{-1} (4.4 Mg ha^{-1}, A&L Analytical Laboratories). Similarly, wheat and fallow received 66.7 kg N ha^{-1}, whereas vetch and Austrian winter pea received 50.4 kg N ha^{-1} in the form of urea, based on calculated N contribution of vetch.

Before planting, burndown herbicides were used to terminate existing vegetation and bio-covers. Either paraquat (1,1-dimethyl-4,4-bipyridinium; 0.3 kg a.i.), glyphosate [*N*-(phosphonomethyl)-glycine; 0.5 kg a.e.], or glufosinate [ammonium (±)-2 amino-4-(hydroxymethylphosphinyl) butanoate] was applied in March each year, prior to corn, soybean, and cotton seeding. One or two post-emergence applications of glyphosate (0.4 kg a.e.) were applied to all plots from May to June annually during Phases I and II, whereas glufosinate (0.3 kg a.i.) was used in Phases III and IV. For cotton, insecticide and crop growth regulation chemical usage was extensive, and annual application dates ranged from June through September. A commercial organophosphate defoliant (brand name Def, a mixture of naphthalene and tribufos *S,S,S*-tributyl phosphorotrithioate), growth regulator (brand name Pix, 1,1-dimethylpiperidinium chloride), and organophosphate insecticide (brand name Bidrin, dimethyl phosphate of 3-hydroxy-*N,N*-dimethyl-cis-crotonamide) were applied several times beginning in June after cotton emergence.

Cotton, corn, and soybean yields were collected per Ashworth, Allen, Saxton, & Tyler, 2016a, 2016b, 2017a). Briefly, cotton was harvested between 10 September and 25 October, corn was harvested between 29 August and 27 September, and soybean was harvested between 23 September and 16 October. For cotton, two center rows were harvested each year with an IH 1822 cotton picker (Case). For corn, two (RECM) or three (MTREC) center rows were harvested per plot each year. For soybean, two (RECM) or four center rows (MTREC) were harvested per plot each year. Measurements taken during harvests were cotton seed weight and corn and soybean weights and grain moisture on a per-plot basis.

2.2 | Soil sampling and analysis

In October 2016, soil samples were collected at both sites from 0- to 15- and 15- to 30-cm depths and were air-dried and ground to pass through a 2-mm sieve. Bulk density (BD, g cm^{-3}) was estimated based on SOC content, according to the Abdelbaki (2018) equation, due to its increased performance to predict BD in U.S. soils. Soil pH was determined using a 1:1 soil mass/deionized water volume mixture, and electrical conductivity (EC) was measured using a 1:2 saturated paste method. Total C was determined via high-temperature dry combustion (weight loss on ignition) using a VarioMacro CN analyzer (Elementar Americas Inc.), and assumed to be equivalent as SOC (Rabenhorst, 1988; Tiessen, Bettany, & Stewart, 1981). Soil tests were also conducted at both depths from each plot to determine contents of P, K, cation exchange capacity, and sodium adsorption ratio (SAR). Samples were ground to pass through a 1-mm sieve on a Wiley soil crusher (Thomas Scientific) and Mehlich-1–extractable nutrients (Mehlich, 1953) were measured by inductively coupled plasma using a 7300 ICP-OES DV (Perkin-Elmer).

2.3 | Soil quality assessment

Soil quality indices were calculated using the SMAF (Andrews et al., 2004). Seven indicators of SQ were used in this study, including soil pH, TOC, BD, soil-extractable P and K, EC, and SAR. This approach agrees with the general SMAF guidelines, which recommends using a minimum of five indicators with at least one each representing soil chemical, physical, and biological properties and processes (Karlen et al., 2008). In this study, chemical indicators are represented by soil pH, EC, extractable P and K, and SAR, since they reflect soil salinity and nutrient availability. Physical effects are represented by BD, which is closely related to soil aeration and hydrologic dynamics. Biological effects are represented by TOC, due to its critical role in nutrient cycling, storage, and energy supplies to edaphic organisms. These indicators were selected based on their relevance for soil functionality and sensitivity to management-induced changes (Doran & Parkin, 1994).

Indicators were scored by transforming the measured values into values between 0 and 1 using algorithms on an Excel spreadsheet, with 0 representing the lowest SQ value and 1 indicating the highest SQ value for each treatment (Andrews et al., 2004; Stott et al., 2011; Wienhold et al., 2009). The scoring curves developed for each potential indicator account for inherent soil properties, climatic factors, cropping history, and selected analytical methods for soil chemical properties. These curves are then scored by the SMAF factor classes. The organic matter factor class 3 (suborder Udalf) was used based on the soil classification and used to score TOC and P for both sites. The texture factor class 3 (silt loam), also based on the soil classification, was used to score TOC, BD, test P, and EC for both sites. The climate factor class 3 (≤170 °C d and ≥550 mm) was included, which is based on the number of degree days and the mean annual temperature of each site, was used to score TOC for both sites. The mineral factor class, which is based on the soil mineralogical composition and required to score BD, was 1 (smectitic) for both sites, due to their active characteristic. The crop and rotation codes were used for pH, P, and EC interpretations, with the latter referring to salt tolerance of a certain crop in rotation. The slope and weathering factor classes were used for scoring P and they were 1 (0–2%) and 3 (slightly weathered), respectively, in both sites. The P and EC codes were used to score the extraction method and they were 1 (Mehlich-1) and 1 (saturated paste) for both sites.

2.4 | Statistical analysis

The score values for each indicator were evaluated individually and as an overall SQI to determine the effect of cropping rotations and bio-covers on SQ. The overall SQI represents the sum of seven indicators equally weighed. Percentage-based values were calculated by dividing SQI by 7, which is the maximum score for this study, and multiplying by 100. As main effects did not differ by location, individual and overall SQ scores were analyzed across locations and soil depths (0–15 and 15–30 cm). Scores were also analyzed across locations and separately per depth. Analysis of variance of individual SQ scores and overall SQI was performed using the SAS MIXED procedure (SAS V9.4; SAS Institute, 2017). Crop rotation, bio-cover, and depth were considered fixed effects, and block and location were considered random effects. When main effects or interactions were found between the explanatory factors, mean separation was performed by the SAS macro "pdmix800" (Saxton, 1998) with Fisher's least significant difference and Type I error rate of 5%. Simple linear regressions between SQI (0- to 15- and 15- to 30-cm soil depth) and Phase III (2010–2013) average crop yields were performed using the SAS REG procedure (SAS V9.4; SAS Institute, 2017), with crop yield considered the dependent variable. Soil quality index observations per depth represents the average value for each crop rotation and bio-cover across locations.

TABLE 2 Analysis of variance of soil quality index (SQI) across locations (Research Education Center, Milan, TN, and Middle Tennessee Research Education Center, Spring Hill, TN) and soil depths (0–15 and 15–30 cm)

Fixed effect	Num DF	Den DF	*F* value	*Pr* > *F*
Rotation	4	214	3.11	.0164
Bio-cover	4	214	0.36	.8345
Rotation × bio-cover	16	214	0.93	.5384
Depth	1	214	199.52	<.0001
Depth × rotation	4	214	1.62	.1711
Depth × bio-cover	4	214	6.20	<.0001
Depth × rotation × bio-cover	16	214	0.70	.7910

TABLE 3 Analysis of variance of soil quality index (SQI) across locations (Research Education Center, Milan, TN, and Middle Tennessee Research Education Center, Spring Hill, TN) per soil depth (0–15 and 15–30 cm)

Fixed effect	Num DF	Den DF	*F* value	*Pr* > *F*
0–15 cm				
Rotation	4	104	6.54	<.0001
Bio-cover	4	104	12.70	<.0001
Rotation × bio-cover	16	104	1.98	.0213
15–30 cm				
Rotation	4	104	3.68	.0076
Bio-cover	4	104	2.03	.0950
Rotation × bio-cover	16	104	0.92	.5449

3 | RESULTS AND DISCUSSION

Differences in SQI across the studied sites were found among soil depths, rotations, and the interaction between soil depth and bio-cover (Table 2). When comparing SQI across locations per soil depth, differences were found among rotations, bio-covers, and the interaction between rotations and bio-covers at the 0- to 15-cm soil depth (Table 3), and among rotations at the 15- to 30-cm soil depth. These results suggest that significant differences were dependent on the model applied for SQ analysis (across depths or per depth). Usually, SQ assessments using SMAF are performed separately per depth (Jokela, Posner, Hedtcke, Balser, & Read, 2011; Karlen, Cambardella, Kovar, & Colvin, 2013; Apesteguia et al., 2017; Cherubin et al., 2016; Veum et al., 2015), due to organic matter and fertility gradients that occur within the soil profile. The absence of significant interactions when analyzing SQ across depths was unexpected, as an increased number of observations (n = 270) would be more prone to show statistical differences compared with the analysis per depth (n = 135).

TABLE 4 Soil quality scores within soil depths, crop rotations and bio-covers across locations (Research Education Center, Milan, TN, and Middle Tennessee Research Education Center, Spring Hill, TN)

	Soil quality scores							
Main effects	**TOC**	**pH**	**EC**	**SAR**	**K**	**P**	**BD**	**SQI**
Depth								
0–15 cm	0.17a[a]	0.83b	0.99a	0.79a	0.96a	0.87b	0.59a	5.23a
15–30 cm	0.06b	0.90a	0.69b	0.48b	0.83b	0.98a	0.55b	4.49b
p value	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Rotation								
Continuous Ct	0.09c	0.89ab	0.83b	0.59a	0.91a	0.95a	0.57b	4.83abc
Ct-Cr	0.11bc	0.87b	0.90a	0.70a	0.93a	0.95a	0.57b	5.03a
Continuous Cr	0.13a	0.93a	0.81b	0.62a	0.91a	0.92a	0.58a	4.88ab
Cr-Sy	0.13a	0.82c	0.85ab	0.64a	0.90a	0.91a	0.58a	4.81c
Continuous Sy	0.11b	0.82c	0.82b	0.65a	0.85b	0.91a	0.57b	4.73c
p value	<.0001	<.0001	.0299	.1457	<.0001	.5602	.0003	.0164
Bio-cover								
Fallow	0.11b	0.87b	0.83a	0.64a	0.87b	0.99a	0.57b	4.87a
Litter	0.13a	0.92a	0.86a	0.62a	1.00a	0.67b	0.58a	4.80a
Pea	0.10b	0.86b	0.84a	0.65a	0.86b	0.99a	0.57b	4.87a
Vetch	0.11b	0.85b	0.85a	0.65a	0.86b	1.00a	0.57b	4.89a
Wheat	0.11b	0.83b	0.84a	0.64a	0.88b	0.98a	0.57b	4.86a
p value	.0004	.0002	.7959	.9081	<.0001	<.0001	.0126	.8345

Note. Continuous Ct, continuous cotton; Ct-Cr, cotton–corn–cotton–corn; Continuous Cr, continuous corn; Cr-Sy, corn–soybean–corn–soybean; Continuous Sy, continuous soybean; TOC, total organic carbon; EC, electrical conductivity; SAR, sodium adsorption ratio; BD, bulk density; SQI, soil quality index.
[a]Numbers followed by the same letter do not differ at $p < .05$.

3.1 | Overall soil quality within soil depths

The surface soil depth (0–15 cm) presented the highest overall SQI across locations, with five out of seven indicators showing greater scores compared with the 15- to 30-cm soil depth (Table 4).When expressed as a percentage basis, SQ at the 0- to 15- and 15- to 30-cm soil depths corresponded to 74.7 and 64%, respectively. Soil surface layers are expected to have increased SQI compared to subsurface, due to the overall increased SOC content and its positive effect on other indicators, such as soil fertility, aggregation, and water retention (Wienhold et al., 2005; Cherubin et al., 2016). Indeed, it was demonstrated that SQI decreases with depth within varying soil types and cropping systems. In previous evaluations on an alluvial-derived soil with sandy loam profile, SQI ranged from 87% at the 0- to 5-cm soil depth to 59.9% at the 20- to 30-cm soil depth, with TOC contents varying between 1.56 and 0.79% (Merrill, Liebig, Tanaka, Krupinsky, & Hanson, 2013).

The higher TOC and K scores at the 0- to 15-cm soil depth (Table 4) reflect an increased TOC and soil fertility at this layer (Supplemental Table S1). Total organic C and soil K scoring curves have the "more-is-better shape," indicating that higher soil C and K contents lead to greater performance of a defined ecosystem function, such as increased nutrient availability for crop productivity (Wienhold et al., 2009). Electrical conductivity and SAR have midpoint optimum scoring curves (Andrews et al., 2004); thus, the highest scores at the 0- to 15-cm soil depth indicate that these soil indicators presented optimum values for this soil layer. Soil pH and P also had midpoint optimum scoring curves; their lower scores at the 0- to 15-cm soil depth indicate that they did not meet the minimum requirements for productivity or exceeded an environmental protection threshold. The highest BD score at the 0- to 15-cm soil depth is due to a lower bulk density in this layer, which agrees with the "less-is-better shape" of the BD scoring curve.

Overall, our results are aligned with previous SQ assessments in long-term no-tillage cropping systems using SMAF. Karlen et al. (2013) evaluated SQ response to long-term (>26 yr) tillage and crop rotation practices in central Iowa and found that soils with loam and clay loam textures under no-tillage were functioning at 72% of their potential at the 0- to 15-cm soil depth. For that study, average TOC and K scores of 0.39 and 0.72 at the 0- to 15-cm soil depth corresponded to TOC and K contents of 2.6% and 121 mg kg^{-1}, respectively. Still, they were considered very low scores and contributed to a reduced SQI under no-tillage when compared with other tillage systems. Assessing the impacts of long-term (31 yr) tillage, cover crop, and fertilization on SQ, Mbuthia et al. (2015) found that silt loam soils under no-tillage had

TABLE 5 Soil quality scores within crop rotations across locations (Research Education Center, Milan, TN, and Middle Tennessee Research Education Center, Spring Hill, TN) per soil depth (0–15 and 15–30 cm)

	Soil quality scores							
Rotation	**TOC**	**pH**	**EC**	**SAR**	**K**	**P**	**BD**	**SQI**
0–15 cm								
Continuous Ct	0.13c[a]	0.89a	0.94a	0.72a	0.93bc	0.88a	0.58c	5.07b
Ct-Cr	0.16bc	0.84ab	0.98a	0.76a	0.97ab	0.88a	0.59b	5.19ab
Continuous Cr	0.21a	0.89a	0.99a	0.76a	0.98a	0.89a	0.60a	5.33a
Cr-Sy	0.19a	0.75c	0.99a	0.78a	0.96ab	0.88a	0.60a	5.14b
Continuous Sy	0.17b	0.78bc	0.98a	0.78a	0.91c	0.86a	0.59b	5.06b
p value	<.0001	<.0001	.0584	.1622	.0001	.9198	<.0001	<.0001
15–30 cm								
Continuous Ct	0.07a	0.90b	0.72bc	0.45a	0.88ab	1.00a	0.55a	4.59ab
Ct-Cr	0.06ab	0.89b	0.82a	0.64a	0.89a	1.00ab	0.55a	4.88a
Continuous Cr	0.06ab	0.96a	0.63c	0.47a	0.83c	0.94c	0.55a	4.43b
Cr-Sy	0.07a	0.89b	0.71b	0.50a	0.84bc	0.94c	0.55a	4.48b
Continuous Sy	0.05b	0.87b	0.67bc	0.52a	0.78d	0.97bc	0.55a	4.40b
p value	.0356	<.0001	.0014	.1067	<.0001	.0021	.0532	.0076

Note. Continuous Ct, continuous cotton; Ct-Cr, cotton–corn–cotton–corn; Continuous Cr, continuous corn; Cr-Sy, corn–soybean–corn–soybean; Continuous Sy, continuous soybean; TOC, total organic carbon; EC, electrical conductivity; SAR, sodium adsorption ratio; BD, bulk density; SQI, soil quality index.
[a]Numbers followed by the same letter within soil depth do not differ at $p < .05$.

a functioning of 68% of their potential at the 0- to 7.5-cm soil depth, not differing from soils under conventional tillage (69%). They pointed out that, regardless of tillage system, cover crop or N-fertilization rate, TOC, and β-glucosidase scores under 0.50 limited SQ, indicating that C and N cycling and storage can still be improved in these soils.

3.2 | Soil quality as affected by crop rotations

Soil quality under distinctive rotations across locations and soil depths ranged from 4.73 to 5.03, corresponding to an overall functioning of 68 and 72% of soil potential capacity, respectively (Table 4). When analyzed across depths, cotton–corn rotations had higher SQI compared to corn–soybean and continuous soybean, not differing from continuous corn and continuous cotton (Table 4). The high EC score for cotton–corn, and the high TOC, pH, and BD scores at continuous corn seemed to contribute to increased SQI under these rotations. Corn–soybean also presented high individual scores for TOC, EC, and BD; however, a low pH score seemed to reduce the overall SQI compared to cotton–corn rotation. The low SQI for continuous soybean is likely a result of a low pH score, along with the lowest K score within rotations (Table 4). These results indicate that small or non-significant differences between individual indicators may lead to significant differences between SQI.

When analyzed across locations per soil depth, SQI at the 0- to 15-cm soil depth varied between 5.06 and 5.19, which corresponded to 72 and 74% of soil potential capacity, respectively (Table 5). At this layer, continuous corn had a high SQI, not differing from cotton–corn rotations. Cotton–corn also had a high SQI at the 15- to 30-cm soil depth (70% of soil potential capacity), not differing from continuous cotton, but higher than the remaining rotations (Table 5). Crop rotations that include species with larger C/N ratios, such as corn, are expected to improve soil quality by increasing SOC content, which is essential for enhancing nutrient cycling, soil aggregation, and microbial diversity. On the other hand, legume-based rotations can increase soil N and reduce applications of inorganic fertilizer, which may improve SQ and contribute to long-term agricultural sustainability (Seman-Varner, Varco, & O'Rourke, 2017). In contrast to our results, Veum et al. (2015) demonstrated that a 17-yr no-till, corn–soybean–wheat rotation had the greatest SQI at the 0- to 5-cm soil depth among annual cropping systems (92%). Our findings showed that corn–soybean rotations have lower SQ compared to continuous corn at the 0- to 15-cm soil depth, which is likely due to the lower pH score (Table 5).

Diverse cropping rotations also play a major role in soil quality by enhancing nutrient cycling and optimizing soil nutrient uptake compared to continuous cropping systems (Karlen et al., 2006; Lal, 2015; McDaniel, Tiemann, & Grandy, 2014), which greatly contributes to improve soil fertility and biodiversity. Continuous soybean had lower SQI compared to cotton–corn and continuous corn sequences when analyzed across depths, which illustrates the importance of diverse cropping systems including plant species with larger C/N ratios for a more sustainable management. Despite being a monoculture, continuous corn had higher TOC, pH,

TABLE 6 Soil quality scores within bio-covers across locations (Research Education Center, Milan, TN, and Middle Tennessee Research Education Center, Spring Hill, TN) per soil depth (0–15 and 15–30 cm)

	Soil quality scores							
Bio-cover	TOC	pH	EC	SAR	K	P	BD	SQI
0–15 cm								
Fallow	0.17b[a]	0.84b	0.96a	0.78a	0.93bc	1.00a	0.59b	5.29a
Litter	0.21a	0.91a	0.99a	0.74a	1.00a	0.33b	0.61a	4.86b
Pea	0.14c	0.82bc	0.95a	0.74a	0.91c	1.00a	0.59c	5.17a
Vetch	0.16bc	0.78c	0.99a	0.78a	0.90c	1.00a	0.59bc	5.22a
Wheat	0.16bc	0.79bc	0.98a	0.78a	0.95b	0.99a	0.59bc	5.25a
p value	.02614	<.0001	.1417	.1419	<.0001	<.0001	<.0001	<.0001
15–30 cm								
Fallow	0.06a	0.89a	0.69a	0.49a	0.81b	0.95a	0.55a	4.46a
Litter	0.06a	0.92a	0.73a	0.49a	0.99a	1.00a	0.55a	4.75a
Pea	0.06a	0.90a	0.72a	0.56a	0.79b	0.97a	0.55a	4.57a
Vetch	0.06a	0.92a	0.72a	0.52a	0.81b	0.99a	0.55a	4.56a
Wheat	0.06a	0.88a	0.69a	0.51a	0.81b	0.96a	0.54a	4.46a
p value	.5160	.3542	.8568	.7813	<.0001	.0907	.2428	.0950

Note. TOC, total organic carbon; EC, electrical conductivity; SAR, sodium adsorption ratio; BD, bulk density; SQI, soil quality index.

[a]Numbers followed by the same letter within soil depth do not differ at $p < .05$.

K, and BD scores compared to continuous soybean (across depths and at the 0- to 15-cm depth; Tables 4 and 5), suggesting that soil fertility and nutrient availability may be limiting factors in continuous soybean systems.

3.3 | Cover crops and poultry litter effects on soil quality

When comparing bio-cover effects across locations and depths, no differences were found between overall SQI values (Table 2); however, several meaningful differences were found between individual scores (Table 4). The highest TOC, pH, K, and BD scores were found for treatments that received poultry litter applications. Poultry litter additions are known to increase SOC and soil fertility in long-term no-tillage systems (Ashworth et al., 2018; Bolan et al., 2010; He et al., 2019; Watts, Torbert, Prior, & Huluka, 2010), which explains the highest TOC and K individual scores. The increased TOC content also seemed to contribute to reduced bulk density levels, leading to the highest BD scores. The application of poultry litter, with consequent P build-up over time, may have caused the lowest P scores when compared to other bio-covers. When applied at adequate timing and proper rates to meet plants' N and P requirements, poultry litter may enhance crop productivity (Ashworth et al., 2018; Endale et al., 2008; Lin, Watts, Van Santen, & Cao, 2018), increase soil microbial community diversity (Acosta-Martinez & Harmel, 2006; Ashworth, DeBruyn, Allen, Radiosevich, & Owens, 2017b; Brooks et al., 2018), and even reduce applications of inorganic fertilizers. However, continuous poultry litter applications may increase soil available P, which may lead to P runoff and eutrophication of water bodies (Schroeder, Radcliffe, & Cabrera, 2004; Sharpley, 1997). The high soil P content (Supplemental Table S1) exceeded the optimum threshold of the P scoring curve, causing a significant reduction in the P score for the poultry litter treatments.

The effects of poultry litter applications on SQ were evidenced when analyzed across locations per soil depth (Table 6). At the 0- to 15-cm soil depth, the lowest SQI value (70%) was observed under poultry litter, with the remaining bio-covers showing greater SQI. The application of poultry litter increased TOC, pH, K, and BD scores compared to the fallow control and the remaining bio-covers; however, the P build-up at soil surface reduced the P score up to 33% of the maximum score (1.00; Table 6), leading to an overall reduced SQI. Conversely, an increased P score (1.00) at the 15- to 30-cm soil depth contributed to improve SQI under poultry litter, not differing from other bio-covers. Thus, these results indicate that poultry litter application may reduce soil quality at the soil surface, but it did not affect soil quality in subsurface, which is a result of low P mobility and accumulation in surface soils under long-term no-tillage systems (Dick, 1983; Rodrigues, Pavinato, Withers, Teles, & Herrera, 2016; Triplett & Dick, 2008).

3.4 | Soil quality as affected by rotations and bio-covers

The interaction between rotations and bio-covers at the 0- to 15-cm soil depth did not indicate treatments with the highest

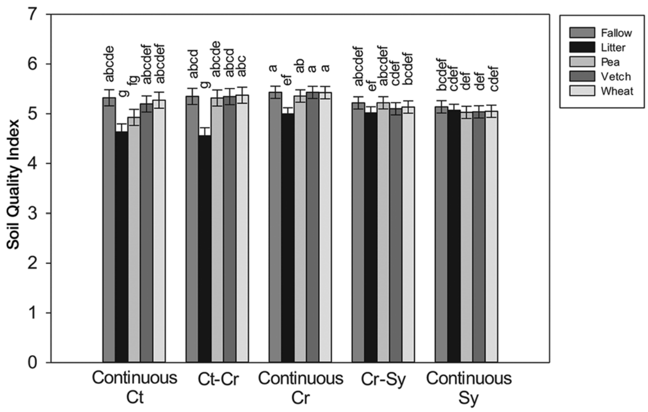

FIGURE 1 Soil quality index within rotations and bio-covers across locations (Research Education Center, Milan, TN, and Middle Tennessee Research Education Center, Spring Hill, TN) at the 0- to 15-cm soil depth. Continuous Ct, continuous cotton; Ct-Cr, cotton–corn–cotton–corn; Continuous Cr, continuous corn; Cr-Sy, corn–soybean–corn–soybean; Continuous Sy, continuous soybean

SQI, although some trends can be identified (Figure 1). Overall, most rotations of continuous corn had higher SQI compared to continuous soybean treatments, not differing from continuous cotton and cotton–corn rotations. Continuous cotton and cotton–corn rotations that received poultry litter had the lowest SQI (4.63 and 4.56, respectively) among treatments, not differing from continuous cotton × Austrian winter pea (4.93). Among continuous corn treatments, reduced SQI was also observed under poultry litter. For corn–soybean and continuous soybean treatments, no differences were found among bio-covers, indicating that poultry litter applications did not negatively impact SQ in soybean-based rotations. Significant differences among treatments were mostly driven by P scores, which had the highest variation (0.08–1.00; Supplemental Table S2).

Our findings highlight the importance of investigating SQ scores individually and separately per depth. The overall SQI differed between rotations but not between bio-covers when investigated across locations and depths, despite the differences between individual scores. When analyzed per depth, significant differences in overall SQI were found between rotations, bio-covers, and their interaction at the 0- to 15-cm soil depth, with individual scores revealing the effects of distinctive conservation practices on SQ. The analysis across depths seems to lessen these effects, whereas the analysis per depth can make them more evident. The proper selection of indicators is another relevant outcome of our study. The overall SQI differences that we obtained relied mostly on soil C and fertility indicators; however, best management practices, such as crop rotation, cover crops, and manure applications, are greatly expected to alter soil N dynamics (Liebman et al., 2018; Sharpley, Smith, & Bain, 1993), microbial biomass and activity (Mbuthia et al., 2015; McDaniel et al., 2014), soil aggregation, and water retention (Blanco-Canqui et al., 2015). Therefore, we suggest that these indicators should be considered in further soil quality studies on long-term cropping systems using SMAF, as they may be more sensitive to interactions between crop rotations and bio-covers.

3.5 | Soil quality and crop yields

A positive relationship was found between SMAF SQI at the 15- to 30-cm soil depth and cotton yield ($R^2 = .48$; $n = 10$; Figure 2b), indicating that improved soil quality contributes to increase cotton yields. Although non-significant, the regression between SMAF SQI at the 15- to 30-cm soil depth and soybean yield showed a positive trend ($R^2 = .30$; $n = 10$; Figure 2f). Non-significant regressions were found between SMAF SQI for both soil depths and corn yield, and for SQI at the 0- to 15-cm soil depth and cotton and soybean yields. The wide confidence intervals are likely a result of the relatively small number of observations used. For this study, SQI data were averaged across locations, except for cotton-based rotations, cultivated only at the RECM site. The SQI data were averaged because the crop yield data used (Phase 3, 2010–2013) were combined across locations. Thus, each SQI observation represents an average value of the respective rotation × bio-cover treatment. Studies with increased number of observations may obtain improved adjustments for the SQI vs. crop yield regressions.

To the best of our knowledge, only few studies have pointed out the positive relationship between soil quality and improved crop yields using SMAF. Investigating cropping systems effects on soil quality in the U. S. Great Plains, Wienhold et al. (2005) found a positive correlation between the SMAF index values and grain yields at two locations ($R^2 = .79$ and .89 for Swift Current, SK, and Mandan, ND, respectively). This indicates that the SMAF index may be helpful for assessing the agronomic goal of soil management. Nakajima, Shrestha, and Lal (2016) demonstrated the on-farm use of a modified SMAF SQI for assessing the effects of tillage and crop rotation on soil quality and crop productivity. For that study, the authors did not include biological factors, and specific weights were given for individual scores based on their contribution to agronomic productivity. They found a positive correlation between SQI values and corn yield ($R = .75$; $n = 30$), indicating that the SQI assessment may be a useful tool for assessing agronomic productivity of soils in the studied region.

In our study, the lack of significant relationships between SQI and crop yields is likely a result of the overall reduced variation in SQI values across rotations and bio-covers, suggesting that the differences in SQ between treatments were not enough to explain the variation in crop productivity. Moreover, poultry litter increased crop yields across locations

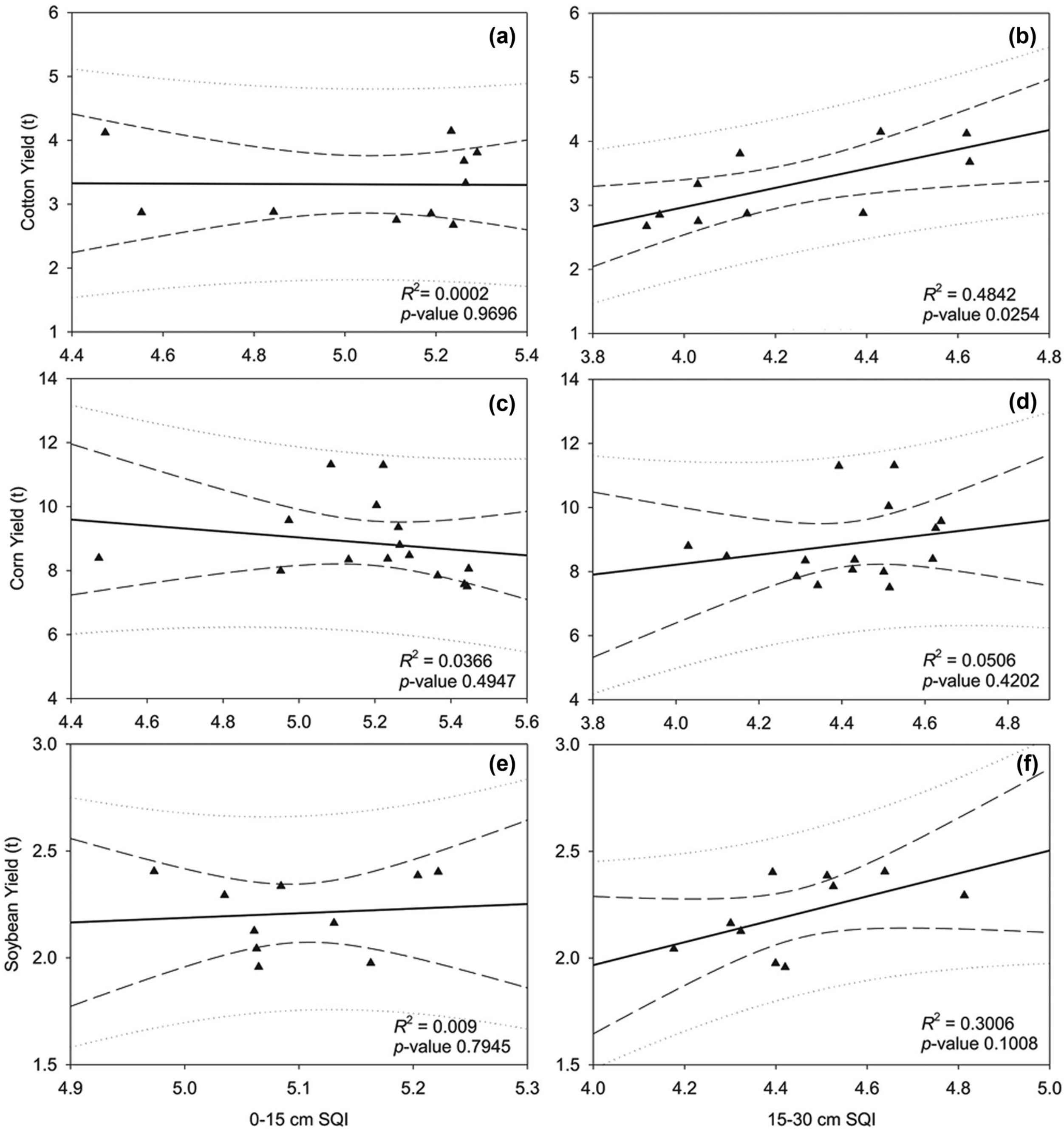

FIGURE 2 Simple linear regressions between soil quality index (SQI) and Phase III (2010–2013) average crop yields across locations (Research Education Center, Milan, TN, and Middle Tennessee Research Education Center, Spring Hill, TN) per depth. (a) SQI at 0–15 cm vs. cotton yield; (b) SQI at 15–30 cm vs. cotton yield; (c) SQI at 0–15 cm vs. corn yield; (d) SQI at 15–30 cm vs. corn yield; (e) SQI at 0–15 cm vs. soybean yield; and (f) SQI at 15–30 cm vs. soybean yield. The continuous line represents the regression fit, the dashed lines represent the 95% confidence limits, and the dotted lines represent the 95% prediction limits

(Ashworth et al., 2016a, 2016b; 2017a), but affected negatively SQ in the 0- to 15-cm soil depth (Table 6), particularly under continuous cotton, cotton–corn, and continuous corn rotations (Figure 1). As previously discussed, poultry litter is known as a valuable source of nutrients, but its continuous application may impair water quality due to potential nutrient runoff. This contrasting behavior probably reduced the likelihood of finding significant relationships between SQI and crop yield at the 0- to 15-cm soil depth. Accordingly, the significant relationship between SQI and cotton yield was found at the 15- to 30-cm depth, on which poultry litter applications had little effect on soil quality.

4 | CONCLUSIONS

This assessment of long-term conservation practices (crop rotations, cover crops, and manure inputs) provided an overview of the effect of cropping rotations and bio-covers on soil quality. It was demonstrated that differences in SQI may depend on the model applied (combined or separately per depth). When combined across depths, rotations of cotton–corn had greater SQ compared to corn–soybean and continuous soybean, not differing from continuous corn and continuous cotton. At the 0- to 15-cm soil depth, continuous corn had greater SQI than continuous cotton and the soybean-based rotations, not differing from cotton–corn rotations. At the 15- to 30-cm soil depth, cotton–corn had greater SQI than continuous corn and the soybean-based rotations, not differing from continuous cotton. Significant differences among rotations were driven by small differences among soil C and fertility scores.

Individual SMAF scores illustrated distinctive effects of bio-covers on SQ, although no meaningful differences were found among overall SQI when analyzed across depths. Poultry litter applications resulted in increased TOC, pH, K, and BD scores, and a low P score as a result of high soil P content. This trend was more evident in the soil surface (0- to 15-cm depth), which had high TOC, pH, K, and BD scores and a very low P score. In the subsurface (15- to 30-cm depth), the application of poultry litter contributed to increased SQI, as the P scores reached the maximum value. Thus, it was demonstrated that poultry litter applications may reduce surface SQ, due to the increased available soil P levels and the potential risk of P runoff and eutrophication of water bodies; however, it did not affect SQ in subsurface layers. These findings indicate that investigating individual SQ scores provides essential information on the effects of conservation practices on soil quality, even when the overall SQI did not present significant differences.

The interaction between rotations and bio-covers at the 0- to 15-cm soil depth did not point out the best management practice for soil quality. It indicated that poultry litter applications reduced SQ within rotations of continuous cotton, cotton–corn, and continuous corn, but it did not affect SQ under soybean-based rotations. The linear regression between the SMAF SQI at the 15- to 30-cm soil depth and cotton yield showed a positive relationship, indicating that improved soil quality contributes to increased crop yields, and that SMAF SQI can be used as a guideline for assessing the effects of soil quality on crop productivity. The SMAF represents a valuable tool for investigating the effects of long-term conservation practices on soil quality, and the information derived from the individual scores provides insights on how changes in soil properties affect the overall SQI. Future studies are suggested for comparison of these SQI findings to other soil quality frameworks.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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