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Amorim, Helen C.S.; Ashworth, Amanda J.; Brye, Kristofor R.; Wienhold, Brian J.; Savin, Mary C.; Owens, Phillip R.; and Silva, Sergio H.G., "Soil quality indices as affected by long-term burning, irrigation, tillage, and fertility management" (2021). *Publications from USDA-ARS / UNL Faculty*. 2524.
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Received: 8 July 2020 | Accepted: 23 October 2020 | Published online: 3 March 2021

DOI: 10.1002/saj2.20188

Soil Science Society of America Journal

SOIL & WATER MANAGEMENT & CONSERVATION

Soil quality indices as affected by long-term burning, irrigation, tillage, and fertility management

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Assigned to Associate Editor Dr. Craig Drury

Abstract

Understanding the impacts of long-term agricultural practices on soil quality (SQ) is key for sustaining agroecosystem productivity. This study investigated conventional and no-tillage (NT), residue burning and no burning, residue level (high and low), and irrigation (irrigated and dryland) effects on soil properties, SQ, and crop yields following 16 yr of a wheat (*Triticum aestivum* L.)–soybean [*Glycine max* (L.) Merr.] double-crop system via the Soil Management Assessment Framework (SMAF). A field experiment was conducted in the Lower Mississippi River Delta region on a silt-loam soil. Bulk density, soil organic C (SOC), total N (TN), pH, electrical conductivity (EC), and soil P and K from the 0- to 10-cm soil depth were used as SQ indicators investigated individually and as an overall soil quality index (SQI). Following 16 yr, residue burning reduced SOC (1.1%) compared with no burning (1.24%). Irrigation resulted in greater soil TN than dryland management systems ($p < 0.05$). Reduced soil pH and extractable soil P and K occurred under NT, high residue, and irrigated treatments. Irrigation increased soybean yields, regardless of the tillage system. Burned, NT–high residue management increased wheat yields (3.45 Mg ha^{-1}). Irrigation reduced SQ because of low EC and K scores. High residue reduced SQ compared with the low residue treatment within NT systems, owing to low pH scores. The SMAF indices identified the impacts of irrigation, NT, and optimal N fertilization on SQ. Monitoring of soil pH, P, and K may be needed to maintain SQ in long-term wheat–soybean systems.

1 | INTRODUCTION

Understanding the impacts of long-term agricultural management practices on soil properties is essential to determine the sustainability of agroecosystems and food production. Conservation agriculture (CA), which is characterized by minimal soil disturbance, residue preservation, and diversification of crop rotations (Hobbs, Sayre, & Gupta, 2008; Lal, 2015a; Reicosky, 2015), can increase soil organic C (SOC) and soil fertility (Jarecki & Lal, 2003; Lal & Kimble, 1997; Peigné, Vian, Payet, & Saby, 2018); improve soil structure, soil biodiversity, and microbial activity (Ashworth, DeBruyn, Allen, Radosevich, & Owens, 2017; McDaniel, Tiemann, &

Abbreviations: BD, bulk density; CA, conservation agriculture; CT, conventional tillage; EC, electrical conductivity; NT, no-tillage; PCA, principal component analysis; SMAF, Soil Management Assessment Framework; SOC, soil organic C; SOM, soil organic matter; SQ, soil quality; SQI, soil quality index; TN, total N.

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Grandy, 2014); increase crop yields (Ashworth, Allen, Saxton, & Tyler, 2016; Jarecki et al., 2018); and reduce erosion (Triplett & Dick, 2008) compared with conventional systems. Because of its multiple benefits, CA has been widely adopted in the past few decades in order to prevent land degradation, improve soil quality (SQ), and sustain crop yields (Lal, 2015b; Kassam et al., 2019).

Conventional tillage (CT), optimal N fertilization, residue burning prior to tillage, and furrow irrigation are traditional management practices associated with wheat (*Triticum aestivum* L.)–soybean [*Glycine max* (L.) Merr.] double-crop (i.e., winter wheat planted the fall before soybean) production systems in the mid-southern United States, particularly in the Lower Mississippi River Delta region of eastern Arkansas (NRCS Soil Survey Staff, 2017). Optimal N fertilization and soil moisture conditions (through irrigation) can increase both plant productivity and the amount of below- and aboveground biomass that can contribute to increased soil organic matter (SOM) and nutrient cycling (Graham, Haynes, & Meyer, 2002; Mazzoncini, Sapkota, Barbieri, Antichi, & Risaliti, 2011; Verkler et al., 2009). Conversely, CT and residue burning may negatively affect soil aggregation and moisture retention (Desrochers, Brye, Gbur, Pollock, & Savin, 2019; Kasper, Buchan, Mentler, & Blum, 2009) and SOM and SOC accumulation (Amuri, Brye, Gbur, Popp, & Chen, 2008; Desrochers et al., 2019; Smith, Brye, Gbur, Chen, & Korth, 2014), which may lead to overall degradation and reduced sustainability of agricultural soils. Because traditional management practices can threaten long-term crop productivity and environmental sustainability, their impacts on SQ need to be better understood.

Soil quality can be defined as the capacity of a soil to perform its functions within ecosystem boundaries, maintaining sustained biological productivity and environmental quality, and promoting plant and animal health (Doran & Parkin, 1994; Karlen et al., 1997). Because of the complexity of the concept, SQ cannot be measured directly in the field or laboratory; however, SQ can be inferred by a combination of soil indicators. Soil quality indicators are soil properties that are sensitive to management-induced changes and reflect functions and ecosystem services (Andrews & Carroll, 2001; Wienhold, Karlen, Andrews, & Stott, 2009). For instance, biological indicators such as SOC, microbial biomass C, and enzyme activity (Mbuthia et al., 2015; Nakajima, Shrestha, & Lal, 2016), and chemical indicators such as P and K (Amorim et al., 2020b; Karlen, Cambardella, Kovar, & Colvin, 2013) are sensitive to changes induced by long-term management practices, and reflect the performance of soils for sustained crop productivity. The integration of individual soil indicators into an overall SQ index (SQI) can provide an overview of management practices at a regional scale and may assist land managers in decision-making processes with respect to land use or function as a guide towards specific management goals (Amorim et al., 2020a; Karlen et al., 2006).

Core Ideas

- Soil quality (SQ) was investigated in a 16-yr wheat–soybean production system
- No burning, high fertility, & irrigation improved soil organic C, total N, & yields
- Reduced SQ under irrigation was linked to lower EC and K scores
- Soil pH was the limiting factor for SQ in a no-tillage–high fertility system
- The SMAF addressed the effects of long-term agricultural practices on SQ

The Soil Management Assessment Framework (SMAF) (Andrews, Karlen, & Cambardella, 2004) is an example of a SQ evaluation tool and has been successfully applied to investigate the impacts of long-term conservation practices on SQ in numerous settings (Veum et al., 2015; Cherubin et al., 2016b; Amorim et al., 2020a; 2020b; Karlen, Veum, Sudduth, Obrycki, & Nunes, 2019). Initially, a minimum dataset with soil biological, physical, and chemical indicators is defined, which can be obtained through principal component analysis (PCA) or expert knowledge (Andrews & Carroll, 2001; Cherubin et al., 2016a). Soil indicators are then transformed into individual scores via SMAF algorithms (i.e., nonlinear scoring curves), which account for inherent and dynamic soil properties, environmental conditions, and crop needs. Finally, individual scores are integrated into an overall SQI (Karlen, Andrews, Wienhold, & Zobeck, 2008; Wienhold et al., 2009), which can be accomplished by adding equally weighted indicators or providing different weights on the basis of the indicator's importance for a specific site and/or management practice.

Since the benefits of CA can vary regionally depending on site-specific characteristics (Pittelkow et al., 2015) and local management practices (Knowler & Bradshaw, 2007), further investigation is needed to understand the linkage between CA and SQ. Long-term studies also provide a unique opportunity to asses agroecosystem sustainability. The objective of this study was to determine (a) the SQ effects of tillage [CT and no-tillage (NT)], residue burning (burning and no burning), residue level (high and low, obtained by differential application of N fertilizer to wheat), and irrigation (irrigated and nonirrigated) on soil properties in the top 10 cm; and (b) crop yields following 16 yr of consistent management in a wheat–soybean double-crop production system, where SQ scores were calculated via the SMAF. It was hypothesized that (a) NT, unburned, irrigated, and high-residue treatments would improve SOM, nutrient concentrations, and soil structure relative to CT, burned, nonirrigated, and low-residue treatments; (b) SQ would be greater under the NT, unburned, irrigated, and high-residue treatment combination than under the CT, burned, nonirrigated, and low-residue treatment combination; and (c) treatments with increased SQ would have increased wheat and soybean yields after 16 yr of consistent management.

2 | MATERIAL AND METHODS

2.1 | Site description

This field study was initiated in the fall of 2001 at the Lon Mann Cotton Branch Experiment Station (34˚44′2.26″N, 90˚45′51.56″W), near Marianna in east-central Arkansas. The study site is located in Major Land Resource Area 134, Southern Mississippi Valley Loess (NRCS, 2013), which is characterized by loess-derived soils of varying thickness on hills and terraces underlaid by alluvial or marine deposits (Brye, 2012). The soil at the site is classified as a Calloway silt loam (fine-silty, mixed, active, thermic Aquic Fraglossudalf; NRCS, 2013) with 16% sand, 73% silt, and 11% clay at the top 10 cm (Brye, Cordell, Longer, & Gbur, 2007). The 30-yr (i.e., 1981–2010) mean annual air temperature and precipitation in the region are 16.6 ˚C and 128.4 cm, respectively, with the 30-yr mean minimum and maximum air temperatures being −0.6 ˚C in January and 32.9 ˚C in July, respectively (NOAA, 2020).

2.2 | Treatments and experimental design

Initially, from 2001 to 2005, field treatments consisted of residue burning and no burning, continuous CT and NT, and high and low wheat-level residue achieved with differential N fertilization of the wheat (Cordell, Brye, Longer, & Gbur, 2007). The burn factor was arranged as a randomized complete block with two replications. The tillage factor was a randomized complete block with three replications, stripped across burn treatments (Figure 1). Residue treatments comprised a split-plot factor within each tillage–burning combination. Thus, the study site originally consisted of 48 3- by 6-m plots with six replications of each tillage–burning–residue treatment combination and was furrow-irrigated from 2001 through to the 2004 soybean growing season. At the start of the 2005 soybean growing season, a water management treatment (i.e., irrigated or dryland) was added as a fourth field treatment factor. For practical reasons, the irrigation treatment was established in the experimental design with a similar blocking structure as the residue burning treatment. Thus, three out of six tillage replications were converted from non-irrigated to irrigated treatments, resulting in six replications

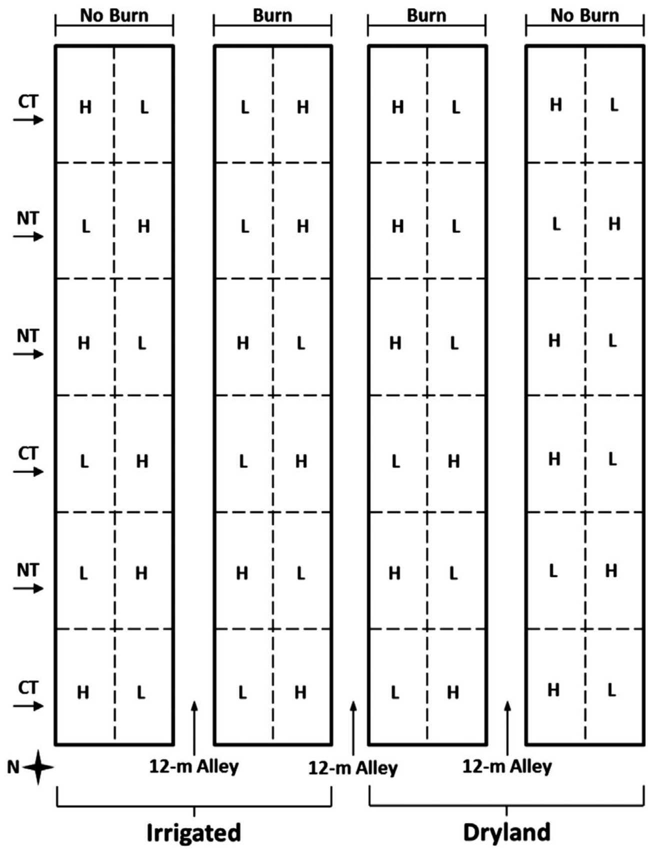

FIGURE 1 Schematic diagram of the experimental design (i.e., burning and no burning), tillage [i.e., conventional tillage (CT) and no-tillage (NT)], residue level [i.e., high (H) and low (L)], and irrigation (i.e., irrigated and dryland) treatments (adapted from Smith et al., 2014). The irrigation and burning treatments had an identical blocking structure, impeding the simultaneous statistical analysis of burning and irrigation

for every burning–tillage–residue treatment combination or six replications for every irrigation-tillage-residue level treatment combination (Smith et al., 2014).

2.3 | Field management

Prior to initiation in 2001, the study site was managed as a continuous soybean cropping system under CT (Cordell et al., 2007). In early to mid-November each year, wheat was drill-seeded at a rate of 90 kg seed ha^{-1} with 19-cm row spacing (Brye et al., 2007). In early March 2002 through to 2004, all plots were manually broadcast-fertilized with 101 kg N ha^{-1} as urea (46% N) with an additional split application of 101 kg N ha^{-1} applied to the high-residue plots in approximately late March. Because of excessive soil moisture in fall 2004, no wheat stand was achieved; thus, no fertilizer-N was applied during the spring of 2005. Beginning in 2006, and in each subsequent year, only the high-residue plots were manually broadcast-fertilized with 56 kg N ha^{-1} as urea (46% N) in late February to early March, followed by a split application of 56 kg N ha^{-1} in approximately late March. After 2006, the low-residue plots received no additional N (Smith et al., 2014).

After the wheat harvest each year, standing wheat stubble within the entire study area was mown to a height of 3 to 6 cm with a tractor-powered, rotary mower (HX10, John Deere, Moline, IL) in order to create a uniform surface layer of residue. After mowing each year, the burning treatment was imposed by manual propane flaming with a handheld propane torch (Bernzomatic TS8000KC, Bernzomatic, Rochester, NY). Following imposition of the burning treatment, the tillage treatment was then imposed prior to soybean planting. Conventional tillage consisted of disking two to three times to a depth of between 7 and 10 cm, followed by surface smoothing with a soil conditioner to break up soil clods (Amuri et al., 2008; Desrochers et al., 2019).

In approximately early to mid-June each year, a glyphosate-resistant soybean cultivar (Maturity Group 5.3 or 5.4) was drill-seeded at 19-cm row spacing at a rate of 47 kg seed ha^{-1}. Potassium fertilizer was applied at recommended rates (University of Arkansas Cooperative Extension Service, 2000) in 2012 (i.e., 134 kg K_2O ha^{-1}) when soil-test K was below optimal. Insects and weeds were controlled according to recommendations on an as-needed basis (University of Arkansas Cooperative Extension Service, 2000). Every year, soybean stubble was left standing prior to planting the subsequent wheat crop (Norman, Brye, Gbur, Chen, & Rupe, 2016).

2.4 | Soil sampling and analyses

In 2018, a single soil sample was randomly collected between wheat maturity and residue burning from the top 10 cm of each plot with a 4.8-cm-diameter stainless steel core chamber. Soil samples were oven-dried for 48 h at 70 ˚C, weighed, and then ground to 2 mm for chemical analyses (Brye, Longer, & Gbur, 2006). Approximately 2 mo after soybean planting, soil samples were collected to assess the effects of field treatments on bulk density. A single soil core 4.8 cm in diameter was randomly collected from each plot with a chamber beveled to the outside to minimize compaction and a slide hammer from the top 10 cm via the methods outlined by Brye et al. (2006). Mid-season soil cores were oven-dried at 70˚C for 48 h and weighed.

Soil pH and electrical conductivity (EC) were determined potentiometrically with an electrode (Orion 9157BN Triode, Thermo Fisher Scientific; Waltham, MA) in 1:2 (w/v) soil-to-water suspension. Soil organic matter concentration was determined by weight loss on ignition after 2 h at 360 ˚C. Total soil C and N concentrations were determined via combustion in a LECO CN-2000 analyzer (LECO Corp., St. Joseph, MI) or by an Elementar Vario MAX Total C and N analyzer (Elementar Americas Inc., Mt. Laurel, NJ). All soil C was assumed to be organic because the soil of the upper solum did not effervesce when treated with dilute hydrochloric acid (Brye et al., 2006). In addition, the soil was mixed with Mehlich-3 extractant in a 1:10 (w/v) soil-to-extractant solution ratio (Mehlich, 1984) and analyzed for extractable P and K concentrations by inductively coupled argon-plasma spectrophotometry (CIROS CCD model, Spectro Analytical Instruments, Mahwah, NJ).

2.5 | Crop yields

Between 2013 and 2018, wheat was harvested with a plot combine in late May to early June; soybean was harvested between late October and mid-November. Wheat and soybean grain samples collected from each plot were air-dried for approximately 3 wk and weighed. Wheat and soybean yields were adjusted to 13% moisture content for yield reporting. The 5-yr average yield (2013–2018) was collected to provide greater confidence in the yield trends and differences among treatments compared with crop yields collected solely in 2018.

2.6 | Soil quality indexing via the SMAF

Soil quality indices were calculated via the SMAF (Andrews et al., 2004) based on soil samples collected in 2018. Six indicators of SQ were used, following the general SMAF guidelines, which recommend 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 the SMAF assessment, soil pH, EC, and extractable P and K represented chemical indicators, since they reflect nutrient availability and affect plant growth. Physical effects were represented by bulk density (BD), which is closely related to soil aeration and water dynamics. Soil organic C was chosen as a biological indicator because of SOC's critical role in nutrient cycling, storage, and energy supply to soil microorganisms. These indicators were selected on the basis of their relevance for soil functionality and sensitivity to management-induced changes (Doran & Parkin, 1994).

Measured values of soil indicators were converted into scores between 0 and 1 via established algorithms in Excel, with 0 representing the lowest SQ value and 1 indicating the largest SQ value for each indicator (Andrews et al., 2004; Stott, Cambardella, Tomer, Karlen, & Wolf, 2011; Wienhold et al., 2009). The algorithms or scoring curves developed for each indicator accounted for inherent soil properties, climatic factors, cropping history, and selected analytical methods for soil chemical properties. These algorithms were described by Andrews et al. (2004) and Wienhold et al. (2009) and are summarized in Table 1 for the soil indicators used in this study.

TABLE 1 Algorithms for interpretation of the Soil Management Assessment Framework (SMAF) soil quality indicators

Indicator[a]	Algorithm	Constant	Site-specific factors
SOC	$y = a/[1 + b \times \exp(-c \times \text{SOC})]$	$a = 1.0$;	$c = f$ (organic matter class, texture, climate)
		$b = 50.1$	
BD	$y = a - b \times \exp(-c \times \text{BD}^d)$	$a = 0.994$	$b, c, d = f$ (texture, mineralogy)
pH	$y = a \times \exp[-(\text{pH} - b)^2/(2 \times c^2)]$	$a = 1.0$	$b, c = f$ (crop)
EC	If $\text{EC}_{1:1} \leq 0.17$, then $y = 5.88 \times \text{EC}_{1:1}$		T[b], b, $m = f$ (crop, texture)
	If $0.17 < \text{EC}_{1:1} \leq T$, then $y = 1$		
	If $\text{EC}_{1:1} > T_{1:1}$, then $y = m \times \text{EC} + b_{1:1}$		
P	If $P \leq$ max (for culture and method), then $y = (a \times b + c \times P^d)/(b + P^d)$	$a = 9.26 \times 10^6$; $c = 1.0$; $d = 3.06$	$b = f$ (crop, SOC, texture, method, slope, weathering class)
	If $P >$ max (for declivity and method), then $y = a - b \times \exp(-c \times P^d)$, and $y = 1$		
K	$y = a[1 - \exp(-b \times K)]$	$a = 1.05$; $b = -0.00981$	$a, b = f$ (crop, texture)

[a]SOC, soil organic C; BD, bulk density; EC, electrical conductivity. [b] T, crop-specific threshold beyond which yield decreases are expected to occur.

The SMAF algorithms were modified by factor classes. The organic matter factor "3" (suborder Udalfs) was based on the soil classification and was used to score SOC and P. The texture factor class "3" (silt loam), also based on the soil classification, was used to score SOC, BD, P, and EC. The climate factor class "3" was based on the number of degree-days and the mean annual temperature of the study site (≤170 ˚C d and ≥550 mm precipitation) and was used to score SOC. The mineral factor class "3" represented soil mineralogy other than smectitic and glassy, and was used to score BD. The crop code "7" (wheat) and the rotation code "5" (soybean) were used for pH, P, and EC interpretations, with soybean being the most sensitive crop in the rotation. The slope and weathering factor classes were used for scoring P and were 1 (0–2%) and 3 (slightly weathered), respectively. The P and EC codes used to score the extraction methods were 2 (Mehlich 3) and 1 (saturated paste), respectively. Although the method used for EC determination in this study was 1:2, SMAF factor classes for EC only account for saturated paste (1) or 1:1 (2). Thus, the factor class "2" was chosen, as the 1:1 EC determination method shows good correlation with the 1:2 EC determination method (Sonmez, Buyuktas, Okturen, & Citak, 2008).

Finally, individual indicator scores were integrated into a SQI by simple addition (SQI_{SA}) and weighted addition (SQI_{WA}) following Equation (1) and Equation (2), respectively:

$$SQI_{SA} : \sum_{i=1}^{n} S_i/n \quad (1)$$

$$SQI_{WA} : \sum_{i=1}^{n} S_i W_i, \quad (2)$$

where S_i was the indicator score, n is the number of indicators integrated in the index, and W_i is the indicator weight. Individual scores were weighted via two approaches: (a) expert knowledge, which considers the contribution of chemical, biological, and physical indicators to distinctive soil functions and environmental services; and (b) PCA, where principal components with large eigenvalues and variables with large factor loadings were considered to best represent the system's attributes and, therefore, received greater weights (Andrews et al., 2001; Andrews, Karlen, & Mitchell, 2002). In this study, expert knowledge weights were established according to their importance to long-term NT systems and their ability to be managed to optimize crop productivity.

Expert knowledge weights were initially obtained by following a framework that provided distinctive weights to soil indicators according to their functions in long-term cropping systems (Karlen et al., 1994; Supplemental Table S1). Afterwards, weights were adapted according to their importance in this study and their ability to be managed towards an environmental or agronomic goal (Table 2). Soil organic C received the largest weight (0.400), because of SOC's key role in water infiltration and availability, maintenance of biological activity, and nutrient storage and cycling. Bulk density reflects soil structure and water dynamics; thus, BD received an intermediate weight (0.200). Fertility and chemical indicators play specific roles in nutrient availability but received low weights (0.100), as these indicators can be more easily managed in agroecosystems than SOC and BD.

A weighted addition was performed with the PCA results, keeping the same proposed weights (Table 2) but ranking them according to the PCA results (Table 3). Principal component analysis is usually applied as a tool for data reduction and selection of a minimum dataset (Andrews & Carroll, 2001;

TABLE 2 Individual indicator weights based on expert knowledge and principal component analysis (PCA)

Indicator[a]	Soil function	Expert knowledge weight[b]	Proposed weight[c]	PCA-based weight[d]
SOC	Accommodate water entry; facilitate water movement and availability; sustain biological activity, plant growth, and crop productivity (nutrient storage and cycling)	0.456	0.400	0.100
BD	Accommodate water entry and facilitate water movement and availability	0.240	0.200	0.100
pH	Sustain plant growth and crop productivity (nutrient availability)	0.060	0.100	0.100
EC	Sustain plant growth and crop productivity (nutrient availability, storage, and cycling)	0.124	0.100	0.200
P	Sustain plant growth and crop productivity (nutrient availability)	0.060	0.100	0.100
K	Sustain plant growth and crop productivity (nutrient availability)	0.060	0.100	0.400

[a]SOC, soil organic C; BD, bulk density; EC, electrical conductivity.
[b]Expert knowledge weight represents a sum of individual weights from Supplemental Table S1.
[c]Proposed weight represents an adaptation of expert knowledge weights assigned to this study.
[d]Greater weights were provided to large factor loadings under Principal Component 1 (PC1).

TABLE 3 Principal component analysis (PCA) of soil indicators used in the Soil Management Assessment Framework (SMAF)

Parameters[a]	Principal components		
	PC1[b]	PC2	PC3
Eigenvalues	2.31	1.19	1.00
Variance explained (%)	38.47	19.87	16.77
Cumulative (%)	38.47	58.34	75.11
Indicators	Eigenvectors		
SOC	0.390	−0.662	0.295
pH	−0.411	0.221	0.852
EC	**0.828**[c]	−0.183	−0.005
P	0.741	0.053	0.428
K	**0.837**	0.349	−0.099
BD	0.229	0.739	0.025

[a]SOC, soil organic C; EC, electrical conductivity; BD, bulk density.
[b]PC, principal component.
[c]Bold values under PC1 were considered highly weighted.

Cherubin et al., 2016a). In this study, principal components with eigenvalues ≥ 1.00 and variables with large factor loadings (within 10% of the largest weight) under Principal Component 1 received greater weights, as they explained a large percentage of data variance and could be regarded as variables that are sensitive to agroecosystem management (Andrews & Carroll, 2001, 2002). The PCA results showed that Principal Component 1 explained approximately 39% of the variance, and that K and EC were the variables with the largest factor loadings under Principal Component 1 (Table 3). Therefore, the largest proposed weight was assigned to K (0.400), an intermediate weight was assigned to EC (0.200), and equally low weights (0.100) were assigned to the other variables (Table 2). When present, SQI values were calculated dividing the SQI by 6, which was the maximum score that could be obtained using six soil indicators and multiplied by 100.

2.7 | Data analyses

Since irrigation was superimposed into the experimental design with a similar blocking structure to the burning treatment in the field study, the two treatments were confounded. Thus, irrigation and burning treatments could not be analyzed together (Desrochers et al., 2019; Smith et al., 2014). For this reason and similar to procedures used by Smith et al. (2014) and Desrochers et al. (2019), two separate three-factor ANOVAs were conducted based on a strip-split-plot design, each one excluding the other confounding factor. The PROC GLIMMIX procedure in SAS version 9.4 (SAS Institute, 2014) was used to evaluate the fixed effects of burning or irrigation, tillage, residue level, and their interactions on soil properties, SQ indices, and grain yields following 16 yr of consistent management, with replications considered as random effects. When appropriate, means were separated by Fisher's LSD at the .05 level. The PROC FACTOR procedure in SAS was used for the PCA analysis and the PROC REG procedure was used for linear regression analyses between 2018 SQI and average crop yields (2013–2018).

3 | RESULTS AND DISCUSSION

3.1 | Effects of long-term management practices: overview

As would be expected, after 16 yr of consistent management, soil properties and crop yields were affected by burning, irrigation, tillage, and residue treatments ($p < .05$; Table 4). Soil organic matter and SOC differed between burning treatments. Soil P differed between tillage treatments. Soil P and K differed between residue levels. Soil P, K, and wheat and soybean yields were affected by irrigation. Soil organic C and TN differed among irrigation–residue combinations, whereas soybean yield differed among irrigation–tillage combinations. Wheat yield differed among burning–tillage–residue treatments, whereas soil pH varied among irrigation–tillage–residue treatment combinations. Soil BD and EC were unaffected by any treatment.

Similar to soil properties and crop yields, selected individual SQ scores and overall SQIs were affected by irrigation and the tillage × residue interaction ($p < .05$; Table 5). The SOC score differed between burning treatments. Soil P scores varied between tillage treatments. Soil P and K scores were affected by residue levels. Soil EC and K scores and overall SQIs, regardless of the indexing approach used, differed between irrigation treatments. Bulk density scores differed between residue levels within burning treatments. Soil quality indices also differed among tillage–residue treatment combinations ($p < .05$; Table 5). Soil pH varied among irrigation–tillage–residue treatment combinations.

3.2 | Biological indicators as affected by long-term management practices

Unburned treatments had greater SOC and SOM concentrations (1.24 and 2.59%, respectively), than the burned treatments (1.10 and 2.34%, respectively; Table 6), thus confirming the initial hypothesis. Residue retention is reported to increase SOC and general soil fertility in surface horizons (Dalal, 1989; Graham et al., 2002; Rasmussen, Allmaras, Rohde, & Roager, 1980), as residue provides an organic substrate and energy for microbes and for increased SOC retention and nutrient cycling (Ashworth et al., 2014; Jarecki & Lal, 2003). Conversely, burning crop residues reduces the amount of plant material returned to the soil, which may lead to a decrease in SOM and SOC over time compared with soils under no-burning management (Norman et al., 2016). As a result of greater SOC, the SOC score was greater under no burning than under burning (Table 6).

The SOC scoring curve has an upper asymptotic form, as soils with increased SOC are more likely to perform their agronomic and environmental functions better (Wienhold et al., 2008). Soil organic C scores usually have lower values than physical and chemical indicators (Amorim et al., 2020b; Mbuthia et al., 2015; Karlen et al., 2013), suggesting that physical and chemical properties are more easily managed towards optimum values or ranges than SOC, but are less dynamic than biological properties (Ashworth et al., 2014). Moreover, these results indicate that CA practices that increase C retention in soils should be prioritized in long-term cropping systems to improve SQ (Reeves, 1997).

When assessing the interactive effects of irrigation and residue level, the irrigated–low-residue treatment had greater SOC concentrations (1.24%) than the nonirrigated–low-residue treatment combination (1.07%)(Figure 2a). Both the irrigated and nonirrigated high-residue treatments had intermediate SOC concentrations. Irrigated treatments, regardless of residue level, had greater TN (0.12%) than nonirrigated treatments, thus supporting the original hypothesis. Under nonirrigated conditions, the high- residue treatment had greater TN (0.08%) than the low-residue treatment (0.07%)(Figure 2b). Properly managed irrigation contributes to increased plant and microbial biomass, which may lead to an overall increase in SOM and nutrient cycling from increased root production than dryland conditions. Increased plant productivity may also improve nutrient uptake, which may reduce nutrient concentrations and availability in soils.

Despite soil N's critical role in soil quality via controlling SOM decomposition and its ease of determination in the laboratory, the current version of SMAF does not include TN as an individual soil indicator. The current version of SMAF includes potentially mineralizable N, which represents the fraction of N easily decomposed by soil microorganisms, which can be considered an indirect measure of N availability (Drinkwater, Cambardella, Reeder, & Rice, 1996). However, potentially mineralizable N is a more complicated laboratory analysis and would probably be determined less frequently than TN. Although not available yet in the current version of SMAF, another N-based indicator to be considered is nitrate-N (NO_3–N). According to Karlen et al. (2008), NO_3–N reflects the residual effects of crop rotations, fertilization strategies, and use of animal manure. Moreover, NO_3-N provides insight into the potential for surface runoff N losses, N leaching to groundwater, and release of nitrous oxide.

Soil N dynamics are expected to be affected by N fertilization and crop rotation (Drinkwater, Wagoner, & Sarrantonio, 1998; Liebman et al., 2018; McDaniel et al., 2014), especially in wheat–soybean double-cropping systems (Norman et al., 2016), thus affecting soil and environmental quality. The SMAF assessments that did not include N-based indicators

TABLE 4 Summary ANOVA of the effects of burning, irrigation, tillage, residue level, and their interactions on selected soil properties at the 0- to 10-cm soil depth and on wheat and soybean yields following 16 yr of consistent management at the Lon Mann Cotton Branch Experiment Station near Marianna, AR, on a silt-loam soil

Source of variation[a]	SOC[b]	TN	SOM	pH	EC	P	K	BD	Wheat yield	Soybean yield
	p-value									
Burning	**.02**[c]	.19	**.01**	.89	.81	.79	.68	.61	**<.01**	.09
Tillage	.07	.31	.18	**<.01**	.07	**.01**	.18	.79	.25	.29
Burning × Tillage	.51	.66	.91	.46	.49	.25	.84	.45	.60	.10
Residue	.63	.45	.62	**<.01**	.54	**<.01**	**<.01**	.80	**<.01**	.25
Burning × Residue	.36	.49	.28	.36	.80	.68	.35	.06	.69	.56
Tillage × Residue	.07	.47	.08	.23	.12	.58	.89	.75	.51	.39
Burning × Tillage × Residue	.84	.39	.64	.77	.47	.62	.96	.48	**.03**	.81
Irrigation	.39	**<.01**	.69	**<.01**	.08	**.03**	**.01**	.32	**<.01**	**<.01**
Tillage	.08	.27	.22	**.04**	.22	**<.01**	.35	.82	.13	.12
Irrigation × Tillage	.89	.80	.89	.87	.89	.16	.38	.66	.18	**<.01**
Residue	.63	.41	.65	**<.01**	.62	**<.01**	**<.01**	.83	**<.01**	.33
Irrigation × Residue	**.04**	**.01**	.12	**<.01**	.58	.74	.54	.24	.07	.45
Tillage × Residue	.08	.43	.10	.14	.19	.58	.93	.78	.56	.47
Irrigation × Tillage × Residue	.35	.10	.33	**.01**	.73	.22	.64	.73	.72	.49

[a]Two sets of three-factor ANOVAs were conducted because of the similar blocking structure for the burning and irrigation treatments.
[b]SOC, soil organic C; TN, total N; SOM; soil organic matter; EC, electrical conductivity; BD, bulk density.
[c]Bold text indicates significant interactions and main effects ($p < .05$).

TABLE 5 Summary ANOVA of the effects of burning, irrigation, tillage, residue level, and their interactions on individual soil quality scores and overall soil quality indices (SQI) at the 0- to 10-cm soil depth following 16 yr of consistent management at the Lon Mann Cotton Branch Experiment Station near Marianna, AR, on a silt-loam soil

Source of variation[a]	SOC[b]	pH	EC	P	K	BD	SQI_{SA}	SQI_{WA}	SQI_{PCA}
	p-value								
Burning	**.02**[c]	.52	.89	.91	.55	.74	.79	.68	.86
Tillage	.06	**.04**	.08	**<.01**	.12	.98	.35	.54	.30
Burning × Tillage	.76	.62	.62	.33	.75	.81	.89	.93	.90
Residue	.58	**<.01**	.89	**<.01**	**<.01**	.63	.09	.14	.07
Burning × Residue	.34	.22	.57	.87	.31	**.02**	.17	.17	.17
Tillage × Residue	.13	**<.01**	.19	.61	.73	.42	**.04**	**.04**	**.05**
Burning × Tillage × Residue	.96	.83	.60	.52	.77	.25	.98	.99	.98
Irrigation	.54	**.03**	**.03**	.09	**.01**	.57	**<.01**	**.02**	**<.01**
Tillage	.06	**<.01**	.23	**.05**	.32	.99	.43	.59	.40
Irrigation × Tillage	.99	**<.01**	.68	.32	.38	.89	.91	.92	.95
Residue	.58	**<.01**	.92	**<.01**	**<.01**	.64	.15	.19	.13
Irrigation × Residue	.06	**<.01**	.39	.94	.81	.06	.24	.19	.28
Tillage × Residue	.13	**<.01**	.29	.63	.83	.44	.08	.08	.09
Irrigation × Tillage × Residue	.27	**<.01**	.89	.33	.77	.95	.91	.83	.92

[a]Two sets of three-factor ANOVAs were conducted because of the similar blocking structure for the burning and irrigation treatments.
[b]SOC, soil organic C; EC, electrical conductivity; BD, bulk density; SQI_{SA}, soil quality index by simple addition; SQI_{WA}, soil quality index by weighted addition; SQI_{PCA}, soil quality index by principal component analysis.
[c]Bold text indicates significant interactions and main effects ($p < .05$).

had limited ability to capture the positive impacts of N fertilization (Mbuthia et al., 2015) and crop rotations on soil quality (Amorim et al., 2020b). The development of a scoring curve for an N-based indicator (e.g., TN) requires (a) compilation of datasets including indicator values and a measure of a specific soil function, such as sustained crop productivity; (b) determination of the mathematical relationship between the indicator and the soil function, considering that low N concentrations are insufficient for plant growth and that high N concentrations can cause leaching and eutrophication of water bodies (Di & Cameron, 2002); and (c) identifying the factors that affect the relationship between TN and sustained crop productivity within each agroecosystem, such as SOM, soil texture, precipitation, slope, and crop rotations (Di & Cameron, 2002; Halvorson, Wienhold, & Black, 2001; Wienhold et al., 2009). Including alternative or additional N-based indicators in SMAF assessments may improve the ability to identify differences in sustainability and SQ among various field treatment combinations in long-term conservation studies.

3.3 | Chemical indicators as affected by long-term management practices

Soils under irrigated, NT, and high-residue treatments had lower soil P concentrations (21.4, 21.2, and 20.4 mg kg^{-1}, respectively), than non-irrigated, CT, and low-residue treatments (23.9, 24.1, and 24.9 mg kg^{-1}, respectively; Table 6). Optimal irrigation and N fertilization are expected to increase plant productivity and crop yields (Fox & Hoffman, 1981; Graham et al., 2002; Yousaf et al., 2016). Increased plant productivity, in turn, may increase nutrient uptake and reduce the soil concentration, which may explain the lower soil P concentration and, consequently, the reduced P scores under NT and high-residue compared with the CT and low-residue treatments. Soil P had a midpoint-optimum scoring curve, indicating that pH values lower or greater than an optimum range impaired the productivity and environmental functions of soils (Wienhold et al., 2009). In this study, the range of optimum soil P concentration was between 28 and 36 mg kg^{-1}, which explains the increased P scores for the CT and low-residue treatments.

Despite uniform K fertilization throughout the study area, lower soil K concentrations were measured under the irrigated and high-residue treatments (60.1 and 64.2 mg kg^{-1}, respectively) than under the nonirrigated and low-residue treatments (78.5 and 74.4 mg kg^{-1}, respectively; Table 6), which may be a result of the increased nutrient uptake by plants, particularly soybean, as soybean has a large K demand (Singh & Reddy, 2017). However, analysis of tissue nutrient concentrations may be necessary to verify if nutrients were being differentially absorbed in the plants or lost by leaching below the 10-cm soil depth that was sampled. The soil K scoring curve had a more-is-better shape, which indicated that increased soil

TABLE 6 Summary of the individual effects of burning, irrigation, tillage, or residue level on soil properties, individual soil quality scores at the 0- to 10-cm soil depth, and crop yields following 16 yr of consistent management at the Lon Mann Cotton Branch Experiment Station near Marianna, AR, on a silt-loam soil

Treatment[a]	SOC		SOM	EC		P		K		Wheat yield[b]	Soybean yield
	%	score	%	$dS\ m^{-1}$	score	$mg\ kg^{-1}$	score	$mg\ kg^{-1}$	score	$Mg\ ha^{-1}$	
Burning											
Bu	1.10 b[c]	0.20 b	2.34 b	0.14 a	0.82 a	22.4 a	0.97 a	70.6 a	0.65 a	2.56 a	2.05 a
NB	1.24 a	0.26 a	2.59 a	0.14 a	0.81 a	22.08 a	0.97 a	67.9 a	0.63 a	2.23 b	1.94 a
Irrigation											
I	1.19 a	0.24 a	2.45 a	0.13 a	0.76 b	21.4 b	0.96 a	60.1 b	0.59 b	2.14 b	2.22 a
NI	1.14 a	0.22 a	2.49 a	0.15 a	0.87 a	23.9 a	0.97 a	78.5 a	0.70 a	2.65 a	1.77 b
Tillage											
CT	1.11 a	0.21 a	2.41 a	0.15 a	0.84 a	24.1 a	0.98 a	70.7 a	0.65 a	2.32 a	2.03 a
NT	1.22 a	0.25 a	2.52 a	0.13 a	0.79 a	21.2 b	0.96 b	67.9 a	0.63 a	2.48 a	1.95 a
Residue											
H	1.18 a	0.24 a	2.49 a	0.14 a	0.82 a	20.4 b	0.96 b	64.2 b	0.62 b	3.02 a	2.02 a
L	1.15 a	0.22 a	2.45 a	0.14 a	0.81 a	24.9 a	0.98 a	74.4 a	0.67 a	1.77 b	1.96 a

[a]B, burning; NB, no burning; I, irrigated; NI, nonirrigated; CT, conventional tillage; NT, no tillage; H, high residue level; L, low residue level; SOC, soil organic C; SOM; soil organic matter; EC, electrical conductivity.
[b]Wheat and soybean yields ($Mg\ ha^{-1}$) represent average values from 2013 to 2018.
[c]Means followed by the same letter do not differ at $p < .05$.

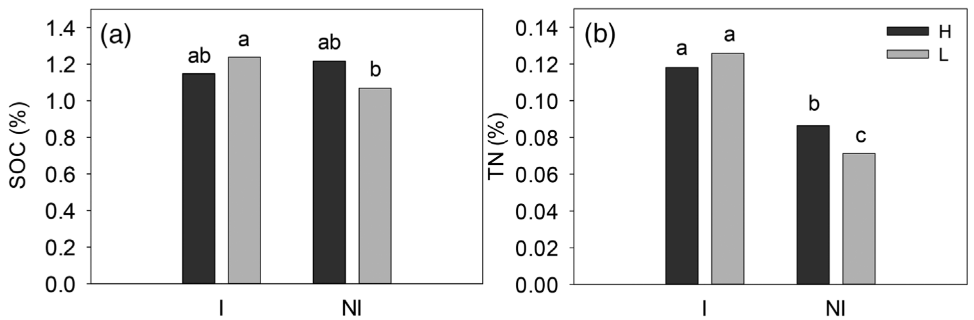

FIGURE 2 Interactive effects of irrigation and residue level on soil organic C (SOC) (a) and total N (TN) (b) in the 0- to10-cm soil depth following 16 yr of consistent management at the Lon Mann Cotton Branch Experiment Station near Marianna, AR, on a silt-loam soil. I, irrigated; NI, nonirrigated; H, high residue level; L, low residue level. Means with the same letter within a panel do not differ at $p < .05$

K concentrations led to increased soil K scores. Thus, the reduced K scores under the irrigated and high-residue treatments reflect their lower soil K concentrations, which were likely to be the result of reduced soil K concentrations following increased plant uptake and/or K leaching below the top 10 cm (Alfaro, Alfaro, Jarvis, & Gregory, 2004).

Probably as a result of reduced soil K concentrations, the irrigated treatment had a reduced EC score (0.76) compared with the nonirrigated treatment (0.87). Although soil EC values did not differ between irrigation treatments ($p > .05$; Table 6), most measured EC values under irrigated conditions were lower than 0.12 $dS\ m^{-1}$, which led to reduced EC scores (lower than 0.73), compared with nonirrigated conditions. Neutral or nonsignificant differences between indicators may lead to significant differences between scores (Amorim et al., 2020b), as a result of an uneven distribution of indicator values in the scoring curve (Wienhold, Andrews, & Karlen, 2005). In the present study, it is worth noticing that EC values were much lower (<0.22 $dS\ m^{-1}$) than those reported to impair crop growth and yields, particularly soybean (Butcher, Wick, Desutter, Chatterjee, & Harmon, 2018; Essa, 2002). Thus, EC values ≥ 0.17 $dS\ m^{-1}$ had a maximum score (1.00). These results are comparable with those reported for long-term double-crop systems: 0.21 $dS\ m^{-1}$ scored 1.00 in a silt-loam soil in the 0- to 5-cm depth interval (Veum et al., 2015) and 0.10 $dS\ m^{-1}$ scored approximately 0.60 (Karlen et al., 2013) in loamy-textured soils in the 0-to 20-cm depth interval.

Greater soil pH (6.85) was observed under the irrigated–CT–low-residue combination, which did not differ from that

TABLE 7 Interactive effects of irrigation, tillage, and residue level on soil pH and respective scores following 16 yr of consistent management at the Lon Mann Cotton Branch Experiment Station near Marianna, AR, on a silt-loam soil

Treatment[a]				pH
Irrigation	Tillage	Residue	pH (1:2 H_2O)	Score
I	CT	H	6.72 ab[b]	0.99 a
		L	6.85 a	0.99 a
	NT	H	6.55 b	0.99 a
		L	6.56 ab	0.99 a
NI	CT	H	6.03 c	0.96 a
		L	6.20 c	0.98 a
	NT	H	5.59 d	0.89 b
		L	6.22 c	0.99 a

[a]I, irrigated; NI, nonirrigated; CT, conventional tillage; NT, no tillage; H, high residue level; L, low residue level.
[b]Means followed by the same letter do not differ at $p < .05$.

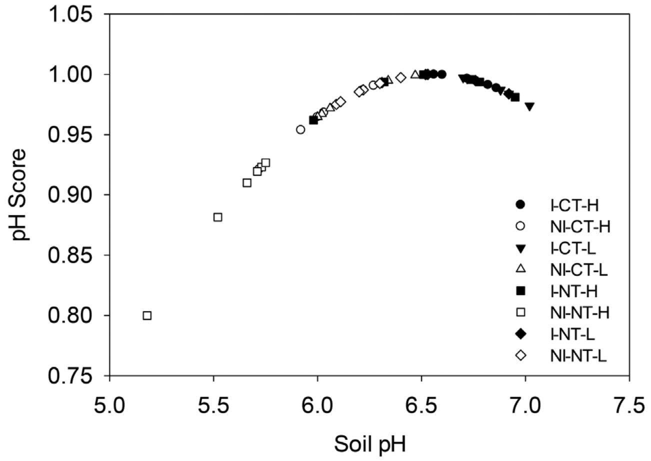

FIGURE 3 Soil pH values and the respective pH scores categorized by irrigation, tillage, and residue level. I, irrigated; NI, nonirrigated; CT, conventional tillage; NT, no-tillage; H: high residue level; L, low residue level

in the irrigated–CT–high-residue (6.72) and irrigated–NT–low-residue (6.56) treatment combinations. The lowest soil pH was measured in the nonirrigated–NT–high-residue combination (5.59; Table 7). Application of large rates of N fertilizers may lead to acidification of upper soil horizons, as NH_4^+ mineralization from inorganic N fertilization has an acidifying effect on soils (Fox & Hoffman, 1981). In addition, N fertilizers applied at rates above the optimum and increased residual inorganic N can negatively affect microbial community and activity (Singh, 2018). Fertilizer-N-induced acidification can be intensified under NT systems (Obour, Mikha, Holman, & Stahlman, 2017; Thomas, Dalal, & Standley, 2007) through the lack of soil disturbance and incorporation of fertilizers in upper horizons. Moreover, the accumulation of organic matter in the topsoil may increase the concentration of organic acids and contribute to reduced soil pH (Limousin & Tessier, 2007). The more alkaline soil pH under the irrigated treatments may be a result of the increased concentrations of Ca and Mg bicarbonates and the elevated groundwater pH used as the irrigation water source in the field study (Amuri et al., 2008).

As a result of having the lowest soil pH (5.59), the nonirrigated–NT–high-residue combination had the lowest pH score (0.89; Table 7). Similar to soil P, soil pH has a midpoint-optimum (i.e., quadratic) scoring curve, for which there is a range of pHs that optimize the performance of soils in terms of productivity and environmental protection. In this study, optimum soil pHs ranged between 6.3 and 6.8 (Figure 3). The nonirrigated–NT–high-residue (Figure 3) treatment combination had soil pHs lower than the optimum range, which led to reduced individual scores. Although scores close to 0.90 can be considered high, the results of this study indicate that some management adjustments may be necessary to improve the performance of NT, dryland, and high-residue agronomic practices.

TABLE 8 Interactive effects of burning and residue level on bulk density (BD) and respective scores following 16 yr of consistent management at the Lon Mann Cotton Branch Experiment Station near Marianna, AR, on a silt-loam soil

Treatment[a]		BD	BD
Burning	Residue	(g cm^{-3})	Score
B	H	1.24 a[b]	0.92 b
	L	1.21 a	0.96 a
NB	H	1.20 a	0.96 ab
	L	1.23 a	0.94 ab

[a]B, burning; NB, no burning; H, high residue level; L, low residue level.
[b]Means followed by the same letter do not differ at $p < .05$.

3.4 | Physical indicators as affected by long-term management practices

The burning–low-residue treatment combination had a greater BD score (0.96) than the burning–high-residue combination (0.92), which did not differ from that of the unburned treatments (Table 8). The increased BD score is a result of a numerically lower BD value (1.21 g cm^{-3}) under the burning–low-residue than under the burning–high-residue treatment combinations (1.24 g cm^{-3}) and reflects the less-is-better shape of the BD scoring curve. However, these results were somewhat unexpected, as high-residue field treatments may increase SOM and contribute to reduced BD in topsoil (Desrochers et al., 2019). In contrast, the impact of residue burning may have negated the SOM effect on BD (Valzano et al., 1997).

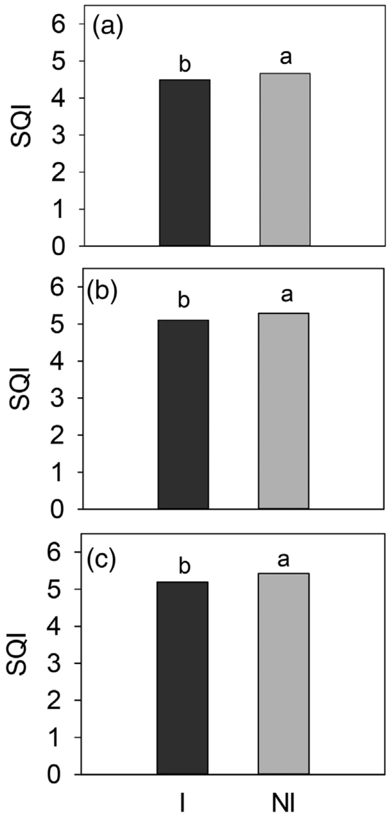

FIGURE 4 Effects of irrigation, averaged across other field treatments, on soil quality indices (SQI) obtained by simple addition (SA)(a), weighted addition (WA)(b), and principal component analysis (PCA)(c) in the 0- to10-cm soil depth following 16 yr of consistent management at the Lon Mann Cotton Branch Experiment Station near Marianna, AR, on a silt-loam soil. I, irrigated; NI, nonirrigated. Means with the same letter within a panel do not differ at $p < .05$

3.5 | Effects of management practices on overall soil quality

After 16 yr of consistent management, SQI was lower under irrigated than nonirrigated conditions when averaged across all other field treatments, regardless of the approach used to integrate the individual scores (Figure 4), thus rejecting the second hypothesis. When obtained by simple addition, SQI under irrigated treatments was 4.49 (Figure 4a), corresponding to 76% of the soil's potential performance (4.49 over 6.00, which is the maximum SQI in a study with six soil indicators). This SQI value increased numerically when obtained by weighted addition (5.10; 85% of potential performance) and by PCA-based weights (5.19; 86% of potential performance) because of the weights provided to each individual factor. The reduced SQI under irrigated conditions was probably the result of lower EC and K scores (Table 6). These results may seem contradictory, since irrigation improved SOC concentrations in low residue systems, and improved N concentrations, regardless of the residue level, compared with nonirrigated systems (Figure 2). Although improved SOC and N levels are usually considered indicators of soil health (Lal, 2016; Ozlu, Sandhu, Kumar, & Arriaga, 2019), it should be noted that irrigation did not affect SOC scores (Table 5), and N is not included in the current version of SMAF. The lower EC and K scores suggest increased crop nutrient uptake as result of greater productivity, which reduced soil EC and K concentrations. These results indicate that irrigation may reduce SQ as a result of reduced soil fertility over time; thus, carefully monitoring and adjusting the soil nutrient levels is recommended to prevent reduced soil fertility in agricultural soils from potential nutrient limitations for subsequent crops in the rotation.

Contrary to what was hypothesized, the results on the interactive effects of tillage and residue level on SQ indicated that the NT–low-residue combination had greater SQ than the NT–high-residue treatment combination, regardless of the indexing approach used (Figure 4). Simple addition SQI results varied between 4.45 and 4.65 of soil potential performance (Figure 5a), corresponding to 74 and 78%, respectively. Weighted-addition SQI ranged from 5.06 to 5.29 (Figure 5b), corresponding to 84 and 88%, respectively, of soil potential performance. Weighted-addition SQI via PCA varied between 5.15 and 5.40 (Figure 5c), which corresponded to 85 and 90% of soil potential performance, respectively. With simple addition (Figure 5a), SQI in the NT–high-residue and CT–low-residue treatment combinations did not differ. Through weighted addition (Figure 5b), SQI in the NT–high-residue combination and both residue levels under CT did not differ. With the PCA-based weights (Figure 5c), SQI in the NT–high-residue combinations was lower than the other tillage-residue treatment combinations. Differences in SQI were mostly driven by soil pH, as soil pH was the only individual soil property score that differed among tillage-residue treatment combinations when averaged across burning treatments (Table 5; $p < .05$).

Soil quality is regarded as a major component for sustained plant productivity and ecosystem functioning and requires an integration of biological, physical, and chemical indicators. Lower soil EC and K were limiting factors for SQ under irrigated treatments. Lower pH limited SQ under the NT–high-residue treatment combination, as soil pH was the only soil indicator that differed among tillage–residue level treatment combinations when averaged across burning treatments (Table 5; $p < .05$). Optimal irrigation, N fertilization, and NT residue management are expected to increase SQ through improved organic matter inputs, soil fertility, and nutrient cycling; however, reduced nutrient concentrations and lower soil pH reduced SQI under these management practices. It should be noted that optimal irrigation, N fertilization, and NT residue management provide multiple benefits to the soil; however, careful monitoring of soil properties may be necessary to align N fertilization and liming requirements with these management practices and thus improve overall SQ.

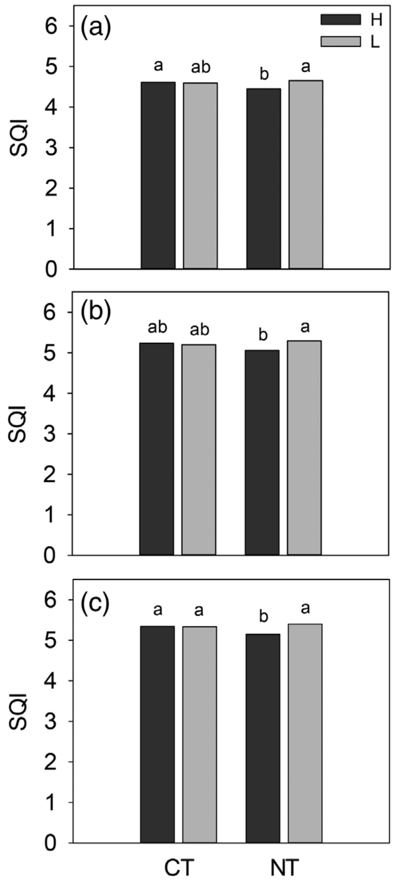

FIGURE 5 Interactive effects of tillage and residue level on soil quality indices (SQI) obtained by simple addition (SA)(a), weighted addition (WA)(b), and principal component analysis (PCA)(c) in the 0-to10-cm soil depth following 16 yr of consistent management at the Lon Mann Cotton Branch Experiment Station near Marianna, AR, on a silt-loam soil. CT, conventional tillage; NT, no-tillage; H, high residue level; L, low residue level. Means with the same letter within a panel do not differ at $p < .05$

The unexpected results in this SMAF assessment may initially suggest that a SQI should not rely on soil chemical or fertility indicators to investigate the effects of long-term agricultural practices on soil quality. However, low EC, K, and pH scores allowed for the identification of potential management issues that, once amended, can improve soil quality and the sustainability of long-term double-crop production systems. Thus, individual SMAF scores and overall SQIs were sensitive to management-induced changes, providing insight on the adjustments needed in each management practice.

3.6 | Crop yields and soil quality

Irrigation increased the 5-yr average (2013–2018) soybean yield regardless of the tillage treatment (Figure 6) but had a negative impact on wheat yields (Table 6), though the wheat crop was not subject to different water management

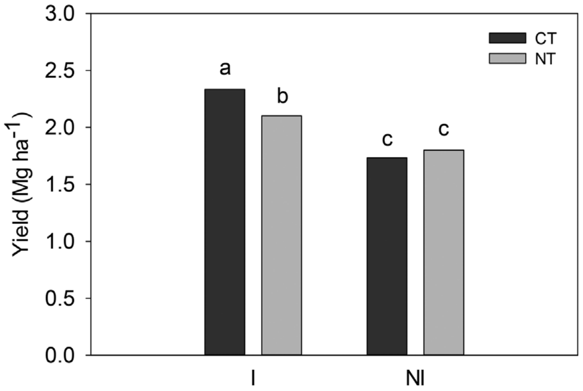

FIGURE 6 Interactive effects of irrigation and tillage on average soybean yields (Mg ha^{-1}) obtained between 2013 and 2018 at the Lon Mann Cotton Branch Experiment Station near Marianna, AR, on a silt-loam soil. I, irrigated; NI, nonirrigated; CT, conventional tillage; NT, no-tillage. Means with the same letter do not differ at $p < .05$

treatments. Irrigated–CT treatments had greater 5-yr average soybean yield (2.33 Mg ha^{-1}) than irrigated–NT treatments (2.10 Mg ha^{-1}). Because of the minimal soil disturbance, NT systems often accumulate SOM and nutrients in the uppermost soil layers, which may contribute to the improved soil fertility, nutrient cycling, and, consequently, crop yields (Ismail, Blevins, & Frye, 1994; Peigné et al., 2018; Tiecher, Calegari, Caner, & Rheinheimer, 2017). However, the crop yield response to NT is variable and may depend on climate conditions (Huang et al., 2018; Pittelkow et al., 2015) and the duration of annual NT management. Reductions in soybean yield under irrigated NT systems may be associated with N immobilization by microbes when decomposing crop residue with large C:N ratios (Lal, 2015a), such as wheat.

The largest 5-yr average (2013–2018) wheat yield was obtained under burning–NT–high residue treatments (3.45 Mg ha^{-1}; Figure 7). The lowest 5-yr average wheat yield was obtained under unburned–CT–low residue treatments (1.50 Mg ha^{-1}), which did not differ from the burned NT–low residue/fertility (1.89 Mg ha^{-1}) and unburned NT–low-residue treatments (1.76 Mg ha^{-1}). Regardless of burning and tillage treatments, 5-yr average wheat yields were always greater under high residue level treatments than low residue level treatments, as hypothesized. This was probably a result of the optimal N fertilization of the wheat crop and improved soil fertility from cumulatively greater overall plant productivity over time for the subsequent soybean crop.

No relationships were identified between simple addition SQI and wheat or soybean yields obtained between 2013 and 2018 ($p > .05$). The lack of correlations was probably a result of the overall reduced variation in SQI values across treatments, suggesting that the differences in SQ, even after more than 16 complete cropping cycles, were not enough to explain the variation in crop productivity (Amorim et al., 2020b).

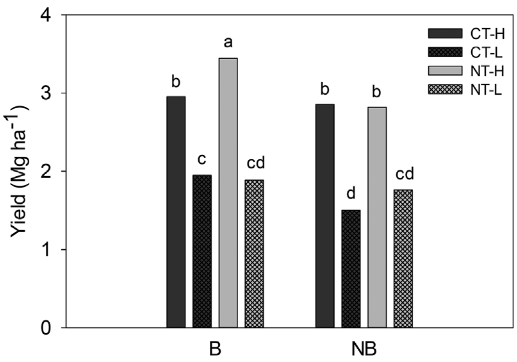

FIGURE 7 Interactive effects of burning, tillage, and residue level on average wheat yields (Mg ha^{-1}) obtained between 2013 and 2018 at the Lon Mann Cotton Branch Experiment Station near Marianna, AR, on a silt-loam soil. B, burning; NB, no burning; CT, conventional tillage; NT, no-tillage; H, high residue level; L, low residue level. Means with the same letter do not differ at $p < .05$

Moreover, the high-residue treatment had a positive impact on wheat yield (Table 6) but had a negative impact on soil pH, P, and K scores, contributing to a reduced SQI under NT–high-residue systems. Therefore, the contrasting behavior probably reduced the ability to identify meaningful relationships between SQI and crop yields.

To date, few studies have demonstrated a positive relationship between SQ and crop yields with the SMAF. Wienhold et al. (2006) reported a positive relationship between the SMAF index values and grain yields for corn (*Zea mays* L.), wheat, and soybean at two locations in the Great Plains region of the central United States on silt-loam and silty-clay-loam soils ($R^2 = 0.79$–0.89). Similarly, Nakajima et al. (2016) used SMAF SQIs to assess the effects of tillage and crop rotation on SQ on loamy and silt-loam soils in Ohio and Michigan, and reported a positive correlation between SQI values and corn yield ($R = 0.75$). A positive relationship ($R^2 = 0.48$) between SQI and cotton (*Gossypium hirsutum* L.) lint yield was shown after 15 yr of consistent management in conservation cropping systems on silt-loam soils in Tennessee (Amorim et al., 2020b); however, no correlations were identified between SQI and corn or soybean yields as a result of excessive nutrient concentration and low P scores. These conflicting results suggest that the SMAF index may be helpful for assessing the agronomic goals of soil management, but greater scores for soil chemical indicators may improve these relationships.

4 | CONCLUSIONS

The impacts of tillage, residue burning, N fertilization/residue level, and irrigation on soil properties and SQIs in the top 10 cm and crop yields were investigated following 16 yr of consistent management in a wheat–soybean double-crop production system in the highly agriculturally productive Lower Mississippi River Delta region of eastern Arkansas. As hypothesized, residue burning reduced SOC and SOM compared with no burning over time. Irrigation increased soybean yields compared with nonirrigated treatments, regardless of the tillage system. High-residue treatments (obtained by optimal N fertilization of wheat) increased wheat yields compared with the low-residue treatment and increased TN under irrigation compared with nonirrigated soybean production. Reductions in soil P and K levels occurred under high-residue and irrigated conditions compared with low-residue and dryland treatments, probably owing to increased plant productivity and nutrient uptake and potential leaching below the top 10 cm. The irrigation–NT–high-residue treatment combination reduced soil pH, which was probably caused by the acidic reaction of N fertilizers associated with the lack of incorporation under NT.

Soil quality indices were calculated with the SMAF and integrated by simple and weighted addition. Weights were attributed to individual soil indicators (i.e., BD, SOC, pH, EC, P, and K) based on their contribution to SQ in long-term cropping systems and based on sensitivity analysis through PCA. Regardless of the approach used, SMAF indices indicated that irrigation contributed to reduced SQ, which was a result of suboptimal soil fertility (i.e., low EC and K scores). High-residue levels led to lower SQ than low residue under NT, which resulted from the low pH score. Soil pH was the SQ limiting factor within tillage and residue treatments. The results indicated that careful monitoring and adjusting of soil fertility may be necessary to capture the benefits of optimal irrigation, N fertilization, and NT residue management and to maintain SQ in long-term wheat–soybean double-crop production systems.

Contrary to what was hypothesized, field treatments with increased SQ did not result in increased crop yields, as no correlations were identified between SMAF SQI and wheat or soybean yields. The lack of SQI–yield correlations was probably caused by the contrasting behavior caused by the high-residue treatment, which reduced soil pH, P, and K but increased crop yields. The SMAF indices provided an overview of the effects of long-term management practices on soil quality, indicating limiting factors for SQ. Constant efforts towards the development and improvement of SQ assessment tools, as well as the inclusion of new indicators, may contribute to more efficient monitoring of soil health and more sustainable agricultural production systems.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

ACKNOWLEDGEMENTS

The authors extend gratitude to Devison Peixoto (UFLA, Brazil) and Faye Smith (USDA-ARS) for helping with statistical analysis and interpretation. Mention of tradenames or

commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA.

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SUPPORTING INFORMATION

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

How to cite this article: Amorim HC, Ashworth AJ, Brye KR, et al. Soil quality indices as affected by long-term burning, irrigation, tillage, and fertility management. *Soil Sci Soc Am J*. 2021;85:379–395. https://doi.org/10.1002/saj2.20188