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Received: 18 June 2020 | Accepted: 5 March 2021 | Published online: 24 May 2021

DOI: 10.1002/saj2.20246

Soil Science Society of America Journal

SOIL & WATER MANAGEMENT & CONSERVATION

Soil health assessment after 40 years of conservation and conventional tillage management in Southeastern Coastal Plain soils

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Assigned to Associate Editor Shannon Osborne.

Abstract

Conservation tillage (CST) and cover crops are important components of soil health management. In the present study, we applied two independent soil health assessment approaches to evaluate the impacts of 40-yr CST and additional 4-yr cover cropping on a range of soil health indicators and the overall soil health in typical southeastern Coastal Plain soils. Soils were collected at 0–15 cm and analyzed for physical, chemical, and biological indicators. The Soil Management Assessment Framework (SMAF) and Cornell's Comprehensive Assessment of Soil Health (CASH) were used to calculate soil health indices. When compared to conventional tillage, 40-yr CST increased active carbon (C) from 301 to 420 mg kg^{-1} and organic nitrogen (N) mineralization potentials from 0.78 to 0.91 mg kg^{-1} d^{-1}, but it reduced soil electrical conductivity from 133 to 101 µs cm^{-1}. No difference in soil aggregate stability, total C, extractable phosphorous and potassium, microbial biomass C, respiration, and glucosidase activities were observed between the two tillage treatments. Cover cropping had no impacts on any measured variables, except that it increased soil total N. Regardless of tillage and cover cropping, both the SMAF and CASH scoring functions suggested no changes in overall soil health. Soil organic C (SOC) was the only indicator positively correlated with both the SMAF and CASH indices, indicating its importance in maintaining the health of the tested soils. Moreover, CASH index recommended improving soil structure and SOC as the management priority to maintain or improve the overall soil health. Increasing organic inputs along with CST is seemingly the optimal management option.

1 | INTRODUCTION

Building healthy and resilient soils is essential to enhance the productivity and sustainability of agroecosystems (Doran & Zeiss, 2000; Kibblewhite et al., 2008; Lal, 2015). Conservation agriculture, driven by minimum soil disturbance, permanent soil covers, and crop rotation (including cover

Abbreviations: AC, active carbon; BD, bulk density; BG, β-glucosidase; CASH, Comprehensive Assessment of Soil Health; CST, conservation tillage; CV, conventional tillage; EC, electrical conductivity; MBC, microbial biomass carbon; OM%, organic matter content; PMN, potentially mineralizable nitrogen; SMAF, Soil Management Assessment Framework; SOC, soil organic carbon; TN, total nitrogen.

cropping), is considered the core principle to increase soil organic carbon (SOC), which in turn is expected to improve physical, chemical, and biological properties of the managed soils (Luo et al., 2010; Palm et al., 2014; Poeplau & Don, 2015). However, permanent soil cover by crop residue retention was found to have positive, neutral, and sometimes negative effects on increasing SOC contents (Liu et al., 2006; Turmel et al., 2015). In the case of conservation tillage management, it often increased top soil bulk density and had limited impacts on increasing SOC in subsurface soils (Luo et al., 2010; Nash et al., 2018). These observed wide differences in the outcomes of soil health management suggests that desired changes in overall soil health can be site specific and dependent on climate, soil types, cropping systems, and management intensity and history (Palm et al., 2014; Turmel et al., 2015).

Quantifying management-induced changes in overall soil health is difficult and most often assessed by analytical approaches. Traditionally, such assessments have focused on individual soil chemical and physical properties (Schoenholtz et al., 2000; Weil et al., 2003). With the increasing recognition of belowground communities, biological indicators have been adopted and routinely used (Cherubin et al., 2016; Norris et al., 2020; Schindelbeck et al., 2008). It is assumed that the selected indicators are linked to various soil properties and functions, either individually or collectively. However, they may not respond to the management practices in similar directions and magnitudes (Bünemann et al., 2018; Kibblewhite et al., 2008). Selecting sensitive soil properties as indicators is therefore critical for an effective soil health assessment.

Although assessing individual indicators is important, especially for those associated with the targeted soil functions or management goals, the development of assessment approaches that integrate multiple physical, chemical, and biological indicators is viewed more applicable for evaluating changes in overall soil health (Bhardwaj et al., 2011; Bünemann et al., 2018; Fine et al., 2017). The following two indices have been developed and commonly used to evaluate the effect of soil management on soil health: the Soil Management Assessment Framework (SMAF) (Andrews et al., 2004) and Cornell's Comprehensive Assessment of Soil Health (CASH) (Moebius-Clune et al., 2016; Schindelbeck et al., 2008). These two soil health indices integrate soil properties underpinning important soil processes (e.g., C transformation, nutrient cycling, and soil structure maintenance), providing logical frameworks to evaluate overall soil degradation or improvement caused by different management practices over time (Amorim et al., 2020; Bhardwaj et al., 2011; Cherubin et al., 2016; Congreves et al., 2015; Kibblewhite et al., 2008).

Both SMAF and CASH use a three-step process to assess soil health, namely (a) selection of a minimum data set based on management objectives and specific soil functions, (b) interpretation of the measured indicators with unique scoring functions, and (c) integration of indicator scores into an overall soil health index (Andrews et al., 2004; Schindelbeck et al., 2008). However, the two approaches differ in their selection of soil indicators and, most importantly, in the scoring functions used to calculate the soil health index (Andrews et al., 2004; Moebius-Clune et al., 2016), providing independent evaluations of the management effects on changes of overall soil health (Bünemann et al., 2018).

Core Ideas

- Two soil health assessment indices were used to evaluate management impacts,
- Forty-year conservation tillage did not improve overall health indices of a sandy soil (0–15 cm).
- Inclusions of 4-yr cover cropping did not improve indices outcomes but increased soil total N.
- Soil organic C was the only measured variable correlated with both soil health indices.
- Improving soil structure and organic carbon content remain the management priorities.

Sandy Coastal Plain soils have poor soil structure, low SOC, and meager soil fertility largely due to natural high temperature and humid conditions that favor clay mineral weathering and eluviation in conjunction with microbial decomposition of SOC exacerbated by historically intensive cultivation (Novak & Busscher, 2013). Therefore, crop residue retention in combination with minimal soil disturbance are considered promising conservation practices to restore SOC while enhancing soil health in these soils. Various studies have demonstrated the improvements of soil structure (Busscher et al., 2011; Hubbard et al., 2013), nutrient availability (Karlen et al., 1989; Motta et al., 2002), and SOC content (Nash et al., 2018; Spargo et al., 2008) resulting from conservation agriculture practices. In the present study we used both the SMAF and CASH indices to assess whether long-term (40 yr) conservation tillage (CST) and additional short-term (4 yr) cover cropping improved overall soil health in typical sandy soils of the southeastern U.S. Coastal Plain, an area responsible for a quarter of U.S. agricultural production (Ruth et al., 2008). Recent studies have demonstrated that long-term CST has caused significant accumulations of SOC, a key component of soil health index, in the top soils (0–5 cm) of the Coastal Plain (Nash et al., 2018; Novak et al., 2020). Yet, the effect of recent adoption of cover cropping on SOC and related soil health indices remains unknown. It was therefore hypothesized that both the 40-yr CST and inclusion of a 4-yr cover cropping could result in improvement of individual functions, such as soil structure maintenance, nutrient recycling, and C transformation, and collectively improve overall soil health.

2 | MATERIALS AND METHODS

2.1 | Site description

The study site is located at the Pee Dee Research & Education Center of Clemson University, Florence, SC (34˚18′ N, 79˚44′ W). Average annual precipitation is 1,186 mm, and average annual high and low air temperatures are 23.8 and 11.1 ˚C, respectively (U.S. Climate Data; https://www.usclimatedata.com/). The experiment was initiated in 1979 to study the impact of tillage (conventional vs. conservation) in combination with crop residue returns on typical southeastern Coastal Plain soils (Hunt et al., 1997). Soils are Norfolk loamy sands (fine-loamy, siliceous, thermic Typic Kandiudults) (USDA Soil Taxonomy classification). The study consists of five adjacent plots paired by conventional and CST (i.e., five field replicates each). Conventional tillage (CV) included disking (0–15 cm) two or three times annually to incorporate crop residues with a one-pass subsoiling (∼42 cm) prior to planting the spring crops, and CST consisted of one-pass, in-row subsoiling only. Corn (*Zea mays* L.) is the only crop consistently planted over the history of the site. In mid-1980s, rotation was adopted with periodic transitions between corn–winter wheat (*Triticum aestivum* L.)–soybean [*Glycine max* (L.) Merr.] and corn–winter wheat–cotton (*Gossypium* L.) systems. Wheat was replaced with cereal rye (*Secale cereal* L.) cover crop in 2003 to determine its rooting effects on SOC accumulation, which was removed from the rotation in 2008 (Novak et al., 2020). Cover crop alongside winter fallow were introduced in 2015 as a split-plot within each main tillage plot, resulting in a total of 20 experimental subplots. However, only the first four field replicates were selected and used in this study (i.e., 16 subplots). Crimson clover (*Trifolium incarnatum* L.) was planted for the first 2 yr, followed by the mixtures of cereal rye, crimson clover, and radish (*Raphanus sativus* L.). This mixture is recommended by the USDA-NRCS and widely used in the region for the purpose of soil health improvement. When necessary, the site was limed and fertilized according to soil testing results from the Agriculture Service Laboratory of Clemson University. All the experimental plots received same fertilization or liming practices when applied. Additional site description, crop rotation, and management practice details can be found in Karlen et al. (1984), Hunt et al. (1997), and Novak et al. (2007, 2020).

2.2 | Soil health indicators

Both the SMAF and CASH provide a long list of potential indicators of physical, chemical, and biological soil health (Andrews et al., 2004; Schindelbeck et al., 2008). Considering the costs of the analyses, relevant to the interested soil functions and processes, and the availability of the scoring functions of the two approaches, at least one indicator was selected to represent the physical, chemical, and biological soil health that relacted to soil structure maintenance, nutrient cycling, and C storage and microbial activitiy (Andrews et al., 2004; Moebius-Clune et al., 2016). Therefore, 11 individual indicators were selected for the SMAF, and eight were chosen for the CASH (Table 1).

2.3 | Soil sampling and quantifications of indicators

Soil bulk densities (BDs) were determined after collecting field samples with a 5-cm diameter AMS soil core sampler (AMS Inc.) at 0–15 cm, followed by drying soils at 60 ˚C to a constant weight. The dried soil weight and core volume were used to calculate the BD (g cm^{-3}). Extra soil cores (2.5 cm in diameter) were randomly collected from each of the four replicate plots (16 plots in total) at the 0-to-15-cm depth (i.e., the tillage layer) prior to the termination of cover crops in 2018. Samples from each plot were composited and transported to the laboratory, where they were sieved (2 mm) after the removal of plant materials and stored at 4 ˚C until used for all the following analyses.

Soil particle-size distribution was estimated with the micropipette method (Miller & Miller, 1987). The stability of macro- (250–2,000 μm) and micro-aggregates (53–250 μm) was analyzed by wet sieving (Márquez et al., 2004; Six et al., 2000). Sand contents (>53 μm) of each aggregate fraction were corrected according to Six et al. (2000). Mean weight diameter was calculated as described by Márquez et al. (2004). The wet macroaggregate stability (AGS for the SMAF; WAS for the SAMF) was calculated by dividing the mass of macro-aggregates by total soil mass (Cherubin et al., 2016).

Total C and N (TN) were determined using oven-dried (60 ˚C) and ground soils with a Carlo-Erba NA 1500 CNS analyzer (Haak-Buchler Instruments). Because the soils are low in carbonates (Novak & Busscher, 2013) Total C was considered total SOC in this study. Organic matter (OM) content was estimated from SOC by applying a factor of 1.72. Soil pH and electrical conductivity (EC) were measured with an Orion Star A325 pH/conductivity meter (Thermo Scientific) in deionized water (1:3 and 1:1 ratio, respectively) after being equilibrated for 30 min. Extractable N was colorimetrically determined after extracting soils with 1 M KCl for 1 h, followed by analyses of NH_4^+ (Verdouw et al., 1978) and NO_3^- (Doane & Horwáth, 2003) in the extracts. Inorganic N was the sum of NH_4^+ and NO_3^-. Phosphorous (P) concentrations were determined with 0.5 M $NaHCO_3$ (pH 8.5) extracts using the molybdate blue–ascorbic acid method (Murphy & Riley,

TABLE 1 Selected physical, chemical, and biological soil health indicators used for Soil Management Assessment Framework (SMAF) and Cornell's Comprehensive Assessment of Soil Health (CASH) approaches and the relevant soil processes

Soil health indicators	SMAF	CASH	Associated soil processes
Physical	AGS	WAS	soil structure maintenance, infiltration, aeration
	BD		
Chemical	pH	pH	nutrient availability and provision
	extractable-K	extractable-K	
	extractable-P	extractable-P	
	EC		
Biological	PMN	PMN	nutrient cycling, C storage, microbial activities, biogeochemical cycling
	respiration (CO_2 production)	respiration (CO_2 production)	
	SOC	OM%	
	MBC	AC	
	BG		

Note. AC, active C; AGS, macro-aggregate stability; BD, bulk density; BG, β-glucosidase activity; EC, electrical conductivity; MBC, microbial biomass C; OM%, organic matter content; PMN, potentially mineralizable N; SOC, total soil organic C; WAS, wet aggregate stability.

1962). Mehlich-3–extractable potassium (K) was analyzed with an inductively coupled plasma spectrometer. Active C (AC) was described as permanganate-oxidizable C after reacting 3 g soils with 50 ml 0.02 M potassium permanganate solution followed by measuring absorbance at 550 nm (Weil et al., 2003).

Microbial biomass C (MBC) was measured by the fumigation-extraction method (Vance et al., 1987; Ye & Wright, 2010). Soil respiration was estimated by incubating rewetted soils in a closed Mason jar (1 L) in the dark at room temperature (20 ± 1 ˚C) for 48 h (Haney & Haney, 2010). The headspace CO_2 concentration was then analyzed with a gas chromatograph (Model 450-GC, Bruker Daltonics). Potentially mineralizable N (PMN) was quantified with anaerobic incubation of soil samples at 30 ˚C for 7 d, followed by 1 M KCl extraction and colorimetric analysis of NH_4^+ in the extracts (Cadisch et al., 1996). The activities of β-glucosidase (BG) were measured using fluorescence (Ye et al., 2019). In brief, soil samples (5 g, dry equivalent) were mixed with 30 ml deionized water and shaken for 20 min and diluted five times for the assays. Approximately 200-μl samples were incubated with 50 μl of substrates at room temperature (20 ± 1 ˚C) for 24 h in 96-well microplates. The test was conducted in triplicates with controls to assess non-enzymatic production. Enzymatic activity was determined by calculating the mean fluorescence reading change over time with a standard curve.

2.4 | Soil health assessment

For SMAF, the observed values of the indicators were transformed into 0 to 1 values with previously published SMAF scoring curves, accounting for region, climate, mineralogy, soil weathering class, soil texture, organic matter, sampling time, crop, and analytical methods (Andrews et al., 2004; Cherubin et al., 2016; Wienhold et al., 2009). Detailed protocols for indicator scoring can be found in Andrews et al. (2004), Wienhold et al. (2009), and Cherubin et al. (2016). The region code and climate class were 2 (humid) and 1 (≥17 ˚C d and ≥550 mm of average annual precipitation), respectively. The mineralogy, slope, and weathering class factors were 3 (1:1 clay and Fe and Al oxides), 2 (2–5% slope), and 2 (high weathering), respectively. Soil texture class was 1 (sand with <8% clay), and organic matter class was 4 (low content). The season and crop codes were 1 (sampling in spring) and 2 (corn), with a rotation code of 5 (soybean). The P method was $NaHCO_3$–extractable (4, Olsen), and the EC method code was 2 (1:1). Overall soil health was calculated as an additive index values by summing all the indicator scores and dividing by the numbers of indicators (Andrews et al., 2004).

For the CASH, individual updated scoring functions for textural groups of coarse soils described by Fine et al. (2017) were used to calculate the scores for respective indicators based on the cumulative normal distribution. The scores were multiplied by 100 to standardize scoring on a 0–100 scale. Overall soil health index was the average of all indicator scores. More details regarding calculating principals and equations for each indicator were described by Moebius-Clune et al. (2016) and Fine et al. (2017). Calculated scores for individual indicators were further rated as five categories: very low (0–20), low (20–40), medium (40–60), high (60–80), and very high (80–100). These scores represent the decreasing orders of management priority on improving or maintaining the condition (Moebius-Clune et al., 2016).

TABLE 2 Measured physical, chemical, and biological properties of soils under long-term conservation management

	Management system[b]				*P* values	
Soil property[a]	**CV**	**CST**	**CC**	**Fallow**	**Tillage**	**Cover crop**
BD, g cm^{-3}	1.44 (0.20)	1.44 (0.03)	1.45 (0.03)	1.43 (0.02)	.83	.58
WHC, g g^{-1}	0.32 (0.01)	0.30 (0.02)	0.32 (0.02)	0.30 (0.02)	.63	.64
AGS, %	20 (1)	20 (2)	20 (2)	21 (1)	.18	.95
MWD, µm	364 (22)	305 (23)	333 (19)	336 (31)	.17	.91
pH	5.71 (0.04)	5.81 (0.08)	5.67 (0.04)	5.85 (0.07)	.11	.10
EC, µs cm^{-1}	133 (15)	101 (10)	123 (12)	110 (16)	.04*	.60
P, mg kg^{-1}	49 (4)	58 (2)	55 (4)	52 (4)	.27	.33
K, mg kg^{-1}	187 (7)	166 (9)	179 (11)	174 (7)	.19	.63
Nin, mg kg^{-1}	7.8 (0.8)	10.1 (0.8)	9.4 (1.1)	8.6 (0.7)	.12	.45
TN, g kg^{-1}	0.69 (0.04)	0.78 (0.04)	0.76 (0.05)	0.72 (0.04)	.12	.04*
SOC, g kg^{-1}	8.72 (0.76)	9.40 (0.66)	9.16 (0.65)	8.95 (0.79)	.43	.07
OM%	15.0 (1.1)	16.2 (1.1)	15.8 (1.1)	15.4 (1.4)	.62	.91
AC, mg kg^{-1}	301 (27)	420 (23)	338 (33)	383 (32)	.04*	.11
PMN, mg kg^{-1} d^{-1}	0.78 (0.04)	0.91 (0.07)	0.90 (0.05)	0.78 (0.07)	.049*	.25
MBC, mg kg^{-1}	453 (59)	475 (57)	451 (53)	477 (62)	.85	.64
Resp, mg C kg^{-1} d^{-1}	299 (20)	259 (18)	292 (11)	267 (26)	.06	.31
BG, mg kg^{-1} h^{-1}	19.2 (3.8)	10.5 (0.5)	17.0 (3.6)	12.8 (2.5)	.14	.13

Note. Values are means with 1 SE ($n = 8$). *P* values ($\alpha = .05$) are provided for the ANOVA of the main effects of tillage and cover crop. No interaction effect was found in all variables.

[a] AC, active C; AGS, macro-aggregate stability; BD, bulk density; BG, β-glucosidase; EC, electrical conductivity; MBC, microbial biomass C; MWD, mean weight diameter; Nin, inorganic N; OM%, organic matter content; PMN, potentially mineralizable N; Resp, respirator CO_2 production; SOC, total organic C; TN, total N; WHC, water holding capacity.

[b] CC, with cover crop; CST, conservation tillage; CV, conventional tillage; Fallow, without cover crop.

*Significant at the .05 probability level.

2.5 | Statistical analyses

All analyses were carried out with JMP Pro 14 (SAS Institute). Analysis of variance of the main effects (i.e., tillage and cover crop) and their interactions were tested with the standard least squares. The DOE-Custom Design function of the JMP was used to construct the model effects accounting for the split-plot design of the experiment (SAS Institute, 2020). No interactions were found for all the measured variables and hence were excluded from the final model. Data were tested for normality by the Normal Probability Plot of Residuals and log-transformed if the transform substantially improved the overall distribution. Pairwise correlation analyses were conducted to determine relationships among all the measured variables. The significance level was set at $\alpha = .05$.

3 | RESULTS

3.1 | Physical, chemical, and biological indicators of soil health

No main factor effects were found in the two physical indicators: BD (range, 1.42–1.46 g cm^{-3}) and AGS (range, 20–21%) (Table 2).

The measured chemical indicators including EC, AC, and TN were significantly affected by the management practices (Table 2). Regardless of cover crop treatment, long-term CST resulted in lower soil EC (101 ± 10 µs cm^{-1}) than CV (133 ± 15 µs m^{-1}). In contrast, higher AC concentrations were observed in conservation (420 ± 23 mg kg^{-1}) versus conventional (301 ± 27 mg kg^{-1}) tillage. No tillage effects were found in SOC, but cover cropping increased soil TN contents from 0.69 ± 0.04 to 0.78 ± 0.04 g kg^{-1} (Table 2). Neither tillage nor cover crop affected soil pH (range, 5.64–5.91), SOC (range, 8.25–10.07 g kg^{-1}), OM content (range, 15.0–16.2%), extractable-P (range, 50–60 mg kg^{-1}), and extractable-K (range, 160–198 mg kg^{-1}).

Regarding measured biological indicators, neither MBC (range, 412–539 mg kg $^{-1}$) nor BG activities (range, 10.2–23.0 mg kg^{-1} h^{-1}) were significantly affected by the main factors. Similar results were observed for respiration (range, 217–316 mg CO_2–C kg^{-1} d^{-1}). However, long-term CST resulted in higher PMN (0.91 ± 0.07 mg kg^{-1} d^{-1}) when compared to CV (0.78 ± 0.04 mg kg^{-1} d^{-1}). Yet, no significant cover crop impacts were observed (Table 2).

TABLE 3 Individual and integrated Soil Management Assessment Framework scores for soils under different management practices

Soil property[a]	Management system[b]				*P* values	
	CV	CST	CC	Fallow	Tillage	Cover crop
Bulk density	0.93 (0.03)	0.91 (0.04)	0.90 (0.05)	0.94 (0.02)	.69	.53
AGS	0.91 (0.02)	0.85 (0.03)	0.89 (0.02)	0.88 (0.03)	.35	.35
pH	0.97 (0.01)	0.97 (1)	0.96 (0.01)	0.98 (0.01)	.88	.15
EC	0.75 (0.07)	0.59 (0.06)	0.72 (0.07)	0.62 (0.07)	.04*	.40
P	1.0 (0)	1.0 (0)	1.0 (0)	1.0 (0)	NA[c]	NA
K	0.88 (0.01)	0.84 (0.02)	0.86 (0.02)	0.86 (0.01)	.18	.76
PMN	0.10 (0.01)	0.17 (0.03)	0.15 (0.02)	0.12 (0.03)	.008*	.42
SOC	0.84 (0.06)	0.90 (0.03)	0.89 (0.03)	0.85 (0.06)	.56	0.76
MBC	1.0 (0)	1.0 (0)	1.0 (0)	1.0 (0)	NA	NA
β-Glucosidase	0.09 (0.03)	0.04 (0)	0.08 (0.02)	0.06 (0.01)	.18	.12
Respiration	1.0 (0)	1.0 (0)	1.0 (0)	1.0 (0)	NA	NA
Overall	0.77 (0.02)	0.77 (0.01)	0.77 (0.02)	0.74 (0.01)	.44	.58

Note. Values denote means with SE ($n = 8$). *P* values ($\alpha = .05$) are provided for the main effects of tillage and cover crop. No interaction effect was found in all variables.

[a] AGS, aggregate stability (percentage of macroaggregates); EC, electrical conductivity; MBC, microbial biomass C; PMN, potentially mineralizable N; SOC, total organic C.

[b] CC, with cover crops; CST, conservation tillage; CV, conventional tillage; Fallow, without cover crops.

[c] Not available.

*Significant at the .05 probability level.

3.2 | SMAF scores

The individual calculated SMAF scores for the selected soil health indicators were not affected by the two management practices, except for EC and PMN scores, in which CST increased PMN scores from 0.10 ± 0.01 to 0.17 ± 0.03 but decreased EC scores from 0.75 ± 0.07 to 0.59 ± 0.06 when compared to CV (Table 3). Respiration, extractable-P, and MBC were all scored 1 (i.e., the highest), and BG scores were the smallest (range, 0.04–0.12). Likewise, there were no main effects on the integrated physical (0.95–0.98), chemical (0.69–0.75), and biological (0.58–0.61) scores as well as on the overall indices (0.71–0.74) (Table 3). Regardless of management practices, the overall SMAF indices were only correlated with SOC ($R^2 = .46$), BD ($R^2 = .38$), and EC ($R^2 = .44$) (Figure 1).

3.3 | CASH scores

Except for extractable-K (scored 100) and respiration (range, 72–95), most of the calculated scores for selected indicators were lower than 40, rated as "low" or "very low," especially for the PMN and P scores (<20), according to the CASH framework (Table 4). No significant main effects were found in the physical and chemical indicator scores (Table 4). Similar impacts were observed in organic matter content (OM%) and respiration. However, the implementations of CST resulted in higher AC and PMN scores. Consistently, cover cropping did not change any of the calculated CASH scores (Table 4). Among all the measured, OM% and AC were the only variables correlated to the overall CASH index (Figure 2).

4 | DISCUSSION

Soil health assessment is essential to evaluate agricultural management practices for sustainable production (Doran, 2002; Laishram et al., 2012; Norris et al., 2020). In the present study, two independent soil health assessment approaches (i.e., SMAF and CASH) were used to evaluate the impact of 40-yr CST and additional 4-yr cover cropping on soil health in a typical southeastern sandy Coastal Plain soil. Both indices suggested no significant tillage (CV vs. CST) and cover cropping (cover cropping vs. fallow) impacts on overall soil health (0–15 cm) (Tables 2–4). These results did not support the hypothesis that both the 40-yr CST and inclusion of a 4-yr cover cropping could result in improvement of individual functions relevant to soil structure maintenance and C transformation and collectively improve overall soil health. The intrinsically low clay contents of the tested soils (i.e., poor structure and low capacity to preserve SOC) and the relatively lower biomass inputs of cover crop mixtures to long-term cash crop residues incorporation likely explain the insignificant impacts.

TABLE 4 Cornell's Comprehensive Assessment of Soil Health scores and rating for individual soil health indicators

Soil property[a]	Management system[b]				*P* values		Rating[c]
	CV	CST	CC	Fallow	Tillage	Cover crop	
WAS	31 (3)	24 (3)	27 (2)	28 (4)	.18	.84	low
pH	34 (5)	45 (8)	30 (5)	48 (7)	.11	.10	low/medium
P	9 (1)	7 (0)	8 (1)	8 (1)	.27	.33	very low
K	100 (0)	100 (0)	100 (0)	100 (0)	.19	.69	very high
OM%	28 (5)	33 (5)	31 (5)	30 (5)	.62	.91	low
AC	24 (4)	44 (4)	31 (5)	41 (6)	.036*	.088	low/medium
PMN	9 (0.6)	11 (1.3)	11 (0.9)	10 (1.2)	.01*	.34	very low
Respiration	92 (3)	84 (5)	93 (2)	83 (5)	.14	.14	high
Overall	47 (2)	50 (2)	47 (1)	50 (3)	.41	.42	medium

Note. Values denote means with SE (n = 8). P values (α = .05) are provided for the main effects of tillage and cover crop.

[a] AC, active C; OM%, organic matter content; PMN, potentially mineralizable N; WAS, wet aggregate stability.

[b] CC, with cover crops; CST, conservation tillage; CV, conventional tillage; Fallow, without cover crops.

[c] If the scores of individual indicators fall into same rating range, only one rating is provided regardless of the treatments. For the pH and AC indicators, the "low" rating is for soils under CV and CC treatments, and "medium" rating is for the CST and Fallow treatments.

*Significant at the .05 probability level.

4.1 | Tillage and cover cropping impacts on physical, chemical, and biological indicators of SMAF and CASH indices

Soil structure, often indicated by aggregate stability (Six et al., 2000), is a key property to soil processes such as water movement, nutrient cycling, and C sequestration (Bronick & Lal, 2005). Compared with CV, CST reduces soil disturbances and hence maintains natural soil aggregation avoiding soil structure degradation (Pagliai et al., 2004). However, in the present study, no significant improvements of aggregate stability were found in CST, even after introducing cover crops for 4 yr (Table 2). The inherent sandy nature and low clay content (3%) of the top soils (0–15 cm) are the result of extensive clay mineral weathering and clay eluviation accelerated by a hot and humid climate (Novak & Busscher, 2013). It is plausible that the lack of "building blocks" (i.e., clay) limits the formation of aggregates in these soils, which was supported by their low mean weight diameter (Table 2).

Soil clay plus silt fraction affect the capacity of soils to stabilize SOC, whereas soil aggregates provide additional physical capacity to protect SOC that can be modified by soil management (Blanco-Canqui & Ruis, 2018; Schmidt et al., 2011; Six et al., 2000, 2004). The CST reduces SOC decomposition by minimizing the accessibility of SOC to microorganisms and their degrading enzymes (Schmidt et al., 2011). However, it has frequently been demonstrated to have positive, but limited, impacts on increasing SOC (Luo et al., 2010). In the present study, CST did not increase SOC stocks in soils at 0–15 cm (Table 2), suggesting the equilibrium between organic matter inputs (i.e., crop residues) and outputs (i.e., microbial respiration) after long-term conservation managements (Novak et al., 2020; West & Six, 2007).

The EC is a measurement of soluble salt concentrations that can be related to soil water availability, chemical supply, and soil structure (Moebius-Clune et al., 2016; Smith & Doran, 1997). In the present study, CST resulted in lower EC values when compared to CV (Table 2), which has also been documented (Dalal, 1989). The lower EC values were likely caused by lower clay mineral weathering intensity under CST. Nutrient availability in agricultural soils is often regulated by applications of lime and fertilizers, resulting in no difference in soil pH and extractable-P and -K upon changes of tillage or cover cropping (Congreves et al., 2015), which was also observed in the present study (Table 2).

Both AC and PMN, along with respiration and enzyme activities, have been widely used to indicate the bulk activities of microbial communities and soil health (Andrews et al., 2004; Bünemann et al., 2018; Fine et al., 2017; Kahlon et al., 2013). The observed different responses of PMN against respiration and BG activities (Table 2) suggested the decoupling of organic N mineralization and SOC decomposition, which has been reported (Bimüller et al., 2014; Tian et al., 2017). The high AC to inorganic N ratio (Table 2) implied that microbial activities were likely more limited by N availability than by C supplies. It was plausible that the demands for N induced higher N-cycling enzyme activities (Luo et al., 2017; Zhao et al., 2018), which was further induced by the CST treatments (Muruganandam et al., 2009; Vazquez et al., 2019), resulting in higher PMN in CST than in CV soils (Table 2).

The inclusion of cover crops to increasing organic inputs by rotating high residue crops were earlier proposed by Novak et al. (2007). However, cover cropping for 4 yr did not increase

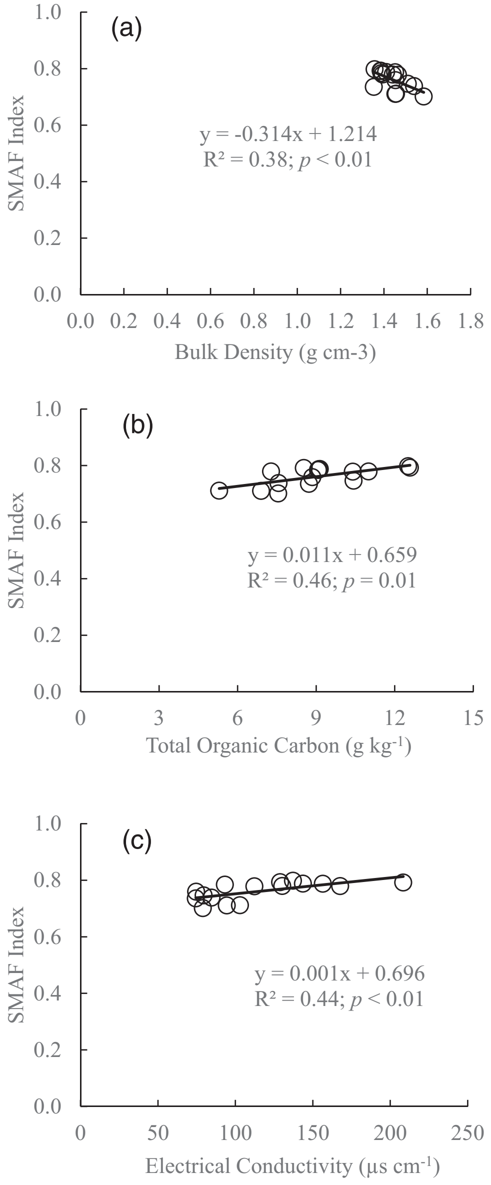

FIGURE 1 Relationship between (a) soil bulk density, (b) total organic carbon, and (c) electrical conductivity and the overall Soil Management Assessment Framework (SMAF) index for a Norfolk soil (0–15 cm).

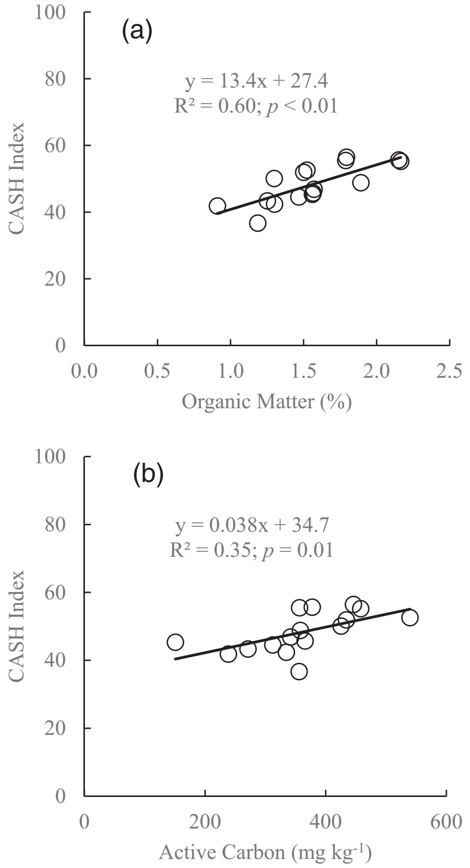

FIGURE 2 Relationship between (a) organic matter and (b) active carbon and the overall Cornell Comprehensive Assessment of Soil Health (CASH) index for a Norfolk soil (0–15 cm).

SOC (Table 2). Annual crop residue retention in the tested soils under corn, soybean, and cotton was estimated and ranged from 3.3 to 6.7 Mg ha^{-1} (Karlen et al., 1984), from 4.0 to 6.2 Mg ha^{-1} (Hunt et al., 2004), and from 2.8 to 6.5 Mg ha^{-1} (Hunt et al., 1998), respectively, all of which were higher than cover crop biomass inputs ranging from 0.4 to 3.1 Mg ha^{-1} (Hunt et al., 1998). It is therefore possible that SOC approached its storage capacity after long-term crop residue returns (Novak et al., 2007, 2020; Poeplau & Don, 2015). Although the amounts of crop residue required to further improve the SOC management outcomes are not well defined (Karlen et al., 1984; Palm et al., 2014), additional research should be carried out to address how much organic inputs are needed to promote further SOC accumulation in these soils approaching SOC storage capacity.

Unlike CST, the inclusion of cover cropping increased TN in soils (Table 2). This positive effect was attributable to the use of cover crop mixtures that helped preserve N in organic forms (Blanco-Canqui et al., 2015; Hubbard et al., 2013). In the present study, crimson clover was planted for the first 2 yr, followed by the mixtures including cereal rye and crimson clover. Whereas cereal rye scavenged soil N into biomass reducing N leaching, crimson clover assimilated atmospheric N via biological fixation, both of which contributed to the observed higher TN in soils (Blanco-Canqui et al., 2015).

4.2 | Assessments of SMAF and CASH indicators

Interpretation of indicator values may require reference values that can be obtained from soils with either least or maximal production and/or environmental performance (Bünemann et al., 2018). In the present study, values of the plots under CV and fallow were used as the reference to estimate the impacts of management practices. In general, SMAF and CASH scores show similar treatment effects. However, the scores for most of the individual indicators are lower for CASH when compared to SMAF (Tables 2 and 3). For instance, the AGS was scored 82–93% of the highest potentials (100%) in the SMAF, but it was rated "low" (<40) by the CASH. A similar pattern was observed for the extractable-P. This difference likely resulted from their different scoring functions and the data used to construct the function (Andrews et al., 2004; Schindelbeck et al., 2008). Although it was not within the scope of our study to compare the effectiveness of SMAF and CASH, the discrepancies between the two indices apparently suggested that region- or site-specific data are needed to develop or improve regional scoring functions allowing reliable and accurate assessments of soil health changes (Bünemann et al., 2018; Fine et al., 2017; Norris et al., 2020; Palm et al., 2014; Roper et al., 2017).

The significant tillage effects on EC, PMN, and AC appeared again in their individual SMAF or CASH scores (Tables 3 and 4), suggesting their sensitivity to assess the changes in those soil health indicators. However, the changes were compromised by insignificant impacts of tillage on the scores of other individual indicators resulting in no changes of overall soil health (Tables 2–4). Weighted, other than additive, approaches have been developed to highlight the ranks of the individual indicators in their importance to soil functions or management goals and interests (Andrews et al., 2002; Congreves et al., 2015). In the present study, all indicators were treated equally in the additive function for overall SMAF and CASH indices. Interestingly, among all the measured variables, only SOC, BD, and EC were correlated with overall SMAF index (Figure 1), whereas OM% and AC correlated with overall CASH index (Figure 2). It is therefore plausible to consider SOC as a suitable endpoint indicator for assessing management impacts on overall soil health, which indeed has been widely used (Bünemann et al., 2018; Cherubin et al., 2016). The correlation of BD to SMAF index further supports the importance of clay content and soil structure.

4.3 | Comprehensive soil health assessment

Assessing soil health changes is difficult due to the complexity of soils and the fact that agricultural management practices most often alter numerous soil characteristics (Bünemann et al., 2018). Despite their difference in scoring functions, both the SMAF and CASH indices suggest that 40-yr CST and 4-yr cover cropping did not change overall soil health in the tested soils (0–15 cm), largely because of the unchanged measured physical, chemical, and biological properties as shown in Tables 2, 3, and 4. These results are not in agreement with several similar health studies (Congreves et al., 2015; Kibblewhite et al., 2008; Turmel et al., 2015). However, in a study in North Carolina's Coastal Plains, no significant differences in the overall CASH score were found between conventional and no-till managed for 17 yr in a Wickham sandy loam (Ultisol) using samples collected from the top 15 cm of soils (Roper et al., 2017).

In the present study, the soils (0–15 cm) were rated by Cthe ASH approach as "medium," with recommended management priority focused on improving soil structure and SOC after 40-yr CST plus 4-yr cover cropping (Moebius-Clune et al., 2016). In this perspective, the results at least suggested that minimal tillage alone was unable to fully address thr current soil issues of the Coastal Plain soils (i.e., low SOC content and poor capacity to protect SOC against microbial decomposition). The SOC stocks in soils are the balance between inputs (i.e., crop residue return and organic amendment) and outputs (i.e., decomposition). It is therefore not surprising that the combination of high-residue crop rotation (including cover crops; i.e., increased inputs) and CST (i.e., reduced outputs) is considered the best management option to increase long-term SOC accumulation (Nash et al., 2018). The capacity of cover crops to increase SOC in agricultural soils are often dependent on the absolute carbon inputs (Poeplau & Don, 2015), which may be more evident in the Coastal Plain regions (as demonstrated in the present study) where the decomposition is very high and much of the soil health is maintained by SOC (Hubbard et al., 2013). Cover crops with high biomass production potentials (e.g., cereal rye and sunn hemp) may be better than others in this perspective.

Improving soil structure (i.e., reducing outputs as decomposition) is another management priority. Recently, Ye et al. (2019) explored and demonstrated the proof-of-concept of clay soil amendment in the fields to support sustainable managements. However, the effects of clay soil sources, ped sizes, and application rates are not studied, and their long-term impacts on soil physio-biogeochemical processes are not known. Meanwhile, the availability of clay soils for application in large scale is also in question. Despite the uncertainties, clay amendments may be a practical strategy to address the aforementioned inherent barriers (i.e., relatively low clay content in the surface soils and the soils' capacity to preserve SOC) (Ye et al., 2019).

In line with similar studies, our results suggested the importance and effectiveness of comprehensive soil health assessments in developing best management practices (Amorim et al., 2020; Laishram et al., 2012; Norris et al., 2020). However, the results also reinforce the concept that soil health tests should be calibrated to better differentiate among soil management effects that vary depending on intrinsic soil limitations (Roper et al., 2017). The CST was often reported to promote significant stratification with increasing SOC observed on top surface soils (Luo et al., 2010; Palm et al., 2014; Turmel et al., 2015). This stratification of SOC was also observed in the tested soils (Novak et al., 2020). Therefore, accounting for this stratification impact may help to better assess the changes of soil health at different soil depths.

Previous research demonstrated a significant SOC increase in the first 15 yr of CST in the tested soils (Hunt et al., 1996); yet it has been suggested that the accumulation may have reached a dynamic static state (Nash et al., 2018; Novak et al., 2020), reducing the increase of SOC over a period of time while minimizing the difference between soils under CST and CV. Therefore, continuous soil health assessment, rather than end-point measurement, may provide additional information to assess management outcomes while revising the guidelines (Bünemann et al., 2018).

5 | CONCLUSION

Forty-year CST resulted in increased soil AC and PMN with decreased soil EC, whereas the incorporations of 4-yr cover cropping did not affect the tillage impacts. As a result, no significant changes of overall soil health were detected by the SAMF and CASH indices. Despite their difference in scoring functions, the two assessment approaches were sensitive enough to describe the quantitative changes in the selected soil health indicators in the present study. However, incorporating a regional dataset is needed to improve the scoring functions and hence the robustness of soil health assessment. Soil organic C was the only measured variable positively correlated to both SAMF and CASH indices, indicating its importance in maintaining soil health of the Coastal Plain soils. Insignificant impacts on the selected soil health indicators were likely attributed to no changes in SOC at the 0-to-15-cm depth upon CST and cover cropping. Indeed, the CASH index rated the tested soils as “medium” and recommended improving soil structure and SOC as the management priority.

ACKNOWLEDGMENTS

This research was part of USDA-ARS National Program 212 Soil and Air, ARS Project 6082-12630-001-00D. Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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How to cite this article: Ye R, Parajuli B, Szogi AA, Sigua GC, Ducey TF. Soil health assessment after 40 years of conservation and conventional tillage management in Southeastern Coastal Plain soils. *Soil Sci Soc Am J*. 2021;*85:*1214–1225. https://doi.org/10.1002/saj2.20246