Reanalysis Validates Soil Health Indicator Sensitivity and Correlation with Long-term Crop Yields

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Soil health (SH) refers to the ability of a soil to function and provide ecosystem services. This study reanalyzes data from long-term agronomic management experiments in North Carolina and addresses previous conclusions regarding the utility of SH test metrics. Data for 15 SH indicators in the Comprehensive Assessment of Soil Health (CASH) framework from three long-term trials in North Carolina were analyzed to assess effects of tillage intensity and organic vs. conventional management. This included four soil biological indicators—organic matter (OM), active carbon (ActC), respiration (Resp), and protein (Prot); four soil physical indicators—available water capacity (AWC), water-stable aggregation (Agstab), surface and subsurface penetration resistance (SurfHard, SubHard); and seven soil chemical (fertility) indicators (P, K, Mg, Fe, Mn, Zn, pH). Corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.) yield data and SH indicator values were correlated using site-specific and multi-site datasets. Long-term management practices most commonly showed significant impacts with AgStab (up to 2.2´), ActC (2.1´), Prot (2.3´), and most chemical indicators. Tillage intensity had a greater impact than organic vs. conventional management and linear regression of multi-year mean corn and soybean yield response to tillage showed significant correlations with eight SH indicators, highest among them ActC, Protein, Resp, and Mn (R^2 = 0.85–0.93). Contrary to previous conclusions, CASH indicators, especially those related to labile C and N, responded well to management practices and showed utility for SH assessment in agronomic trials.

Abbreviations: ActC, active carbon, also known as permanganate oxidizable carbon, POXC; AgStab, water stable aggregation; AWC, available water capacity; CASH, Comprehensive Assessment of Soil Health; ConvTill, conventional tillage; HSHT, Haney Soil Health Test; NC, North Carolina; NCDACS, North Carolina Department of Agricultura and Consumer Services; NoTill, no tillage; OM, organic matter; Resp, respiration during a 4-d incubation; SMAF, Soil Management Assessment Framework; SurfHard, penetration resistance within the 0- to 15-cm depth range; SubHard, penetration resistance within the 15- to 45-cm depth range; SH, soil health; SOM, soil organic matter.

Core Ideas

- **Soil health metrics were sensitive in North Carolina soils.**
- **Tillage intensity and fertility practices were especially differentiated by biological soil health metrics.**
- **Soil health metrics associated with labile organic matter correlated well with crop yields.**

Healthy well-functioning soils that enhance water and air quality, support human health and habitation, and sustain plant and animal productivity are essential to ensuring a sustainable future for an ever-growing global population (Karlen et al., 2003; Karlen and Rice, 2015). Soil health refers to the ability of a soil to perform such functions based on its inherent and dynamic characteristics (Karlen et al., 1997; Andrews et al., 2004; Idowu et al., 2009). Therefore, within the context of land use and management goals, SH represents an understanding of this resource as a dynamic, complex, and living system (Doran and Zeiss, 2000). The terms "soil quality" and "soil health" are used interchangeably in the literature and can be considered equivalent (Bünemann et al., 2018), but within the past 5-yr stakeholder audiences and media sources have shown a preference for the latter term, which we use herein.

Soil Sci. Soc. Am. J. 83:721–732
doi:10.2136/sssaj2018.09.0338
Received 18 Sept. 2018.
Accepted 10 Feb. 2019.
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The assessment of SH can be used as an indicator of sustainable land management (Doran and Jones, 1996; Karlen et al., 1997). Traditional soil testing was and continues to be essential, but it primarily focuses on soil chemical property measurements (i.e., pH and exchangeable or extractable nutrient concentrations) needed to evaluate soil fertility (Moebius-Clune et al., 2016). Without question, traditional soil testing and plant analysis have proven useful for increasing agricultural production, but the narrow focus on soil chemical properties and processes has been regarded as a contributor to physical and biological soil degradation (Tilman et al., 2002; Andrews and Carroll, 2001). The concept of SH embraces a new comprehension of how soils function. It includes an understanding of the physical, biological, and chemical interactions that go well-beyond soil nutrient quantities, and is needed to diagnose and quantify critical dynamic and inherent soil properties and processes (Doran and Safley, 1997).

The Soil Management Assessment Framework (SMAF) was developed by Andrews et al. (2004) as a comprehensive tool that is sensitive to textural class, suborder soil organic matter (SOM) content, Fe_2O_3 content, mineral class, climate, weathering class, slope, sampling time, crop sequence, P analytical method and EC analytical method to evaluate how land management practices impact soil functions (i.e., physical, chemical, and biological soil processes). Subsequently, the CASH framework, initially referred to as the Cornell Soil Health Test (CSHT), was developed based on the same paradigm and designed as a practical framework that directly meets agricultural land manager and applied researcher needs. A CASH analysis emphasizes identification of specific soil constraints within agroecosystems, thereby aiding in the selection of land management solutions to increase productivity and minimize environmental impact (Idowu et al., 2009). The utility of CASH indicators was initially evaluated based on the relevance to soil functions/processes, sensitivity to land management decisions, analytical cost, reproducibility of measurements, sampling requirements, and potential to be estimated by statistical correlation or detected using sensors (Moebius et al., 2007; Moebius-Clune et al., 2016).

The CASH framework was originally calibrated for soils within the northeastern USA, but more recently has been applied to other geographic regions. A recent regional-scale analysis of CASH showed significant SH differences between Midwestern, Northeastern, and Mid-Atlantic soils that were attributed in part to differences in farming systems (Fine et al., 2017). Soil health studies using CASH have also been conducted at the landscape scale (Moebius-Clune et al., 2011; Svoray et al., 2015) and plot scale (Idowu et al., 2009; Congreves et al., 2015; Kinoshita et al., 2017; Nunes et al., 2019), demonstrating that it can effectively detect differences among agronomic management practices at multiple spatial levels and with different types of soil. Similarly, the SMAF has been successfully used for SH (soil quality) analysis in Brazil (Cherubin et al., 2016), Spain (Apesteguía et al., 2017), and for many different soil management comparisons throughout the USA (e.g., Veum et al., 2015; Hammac et al., 2016; Ippolito et al., 2017).

Roper et al. (2017) assessed the utility of CASH as well as the Haney Soil Health Test (HSHT; Haney et al., 2006) and a standard test by the North Carolina Department of Agriculture and Consumer Services (NCDACS; Hardy, 2014) using long-term experiments in three physiographic regions of North Carolina (NC). This included an evaluation of CASH's ability to detect effects of long-term tillage practices and organic vs. conventional management, as well as an analysis of correlations between SH indicators and crop yield. Regarding the latter, few studies have been able to quantify positive relations between SH and crop yield, which is ostensibly a critical issue for farmer adoption. Contrary to most previous studies using either CASH or the SMAF, the authors concluded that SH indicators generally did not differentiate among agronomic management systems, and moreover that SH scores did not show any correlation with crop yield. Those conclusions have recently been cited by others (e.g., Rinot et al., 2019).

Questioning those conclusions based on multiple decades of experience in numerous geographic regions, we decided to reexamine the data and determine whether the research procedures, data analysis approach, or other factors negatively influenced the conclusions. We concluded that the Roper et al. (2017) data clearly document management effects with CASH indicators and demonstrate positive correlations between SH indicators and yields of corn and soybean, an elusive goal of past studies. This suggests that, in line with recent studies (Congreves et al., 2015; Kinoshita et al., 2017; Nunes et al., 2019), the use of CASH or SMAF indicators may in fact be quite valuable for evaluating agronomic practices in programs such as those being coordinated by the Soil Health Partnership (SHP) [https://www.iowacorn.org/corn-production/environmental/soil-health-partnership], Soil Health Institute (SHI) [https://soilhealthinstitute.org/soil-health-research], USDA-NRCS Soil Health Division (SHD) [https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/assessment/], and Foundation for Food and Agricultural Research (FFAR) [https://foundationfar.org/challenge/healthy-soils-thriving-farms/]. Our goal therefore was to perform a rigorous re-analysis of the above-mentioned NC dataset addressing concerns with the research procedures and thereby determining: (i) effects of long-term agronomic management practices on CASH indicators, (ii) relationships between CASH indicators and crop yield for a range of tillage practices, and (iii) the overall utility of the CASH framework for assessing agronomic management practices. We are not addressing the results or conclusions related to the HSHT and NCDACS tests in the Roper et al. (2017) study which have a narrower focus than either CASH and were not available in the supplemental information.

MATERIALS AND METHODS

Research Trials

Data for this analysis were derived from Roper et al. (2017; Table S1 therein), which contained the measured values of the CASH indicators for three long-term experiments conducted within coastal plain, piedmont, and mountain physiographic regions of NC. These soil provinces have variable soil genesis and properties that are reflected in inherent characteristics like texture and mineralogy, as well as distinct climate differences. Corn and soybean yield data were derived from Table 7 (Roper et al., 2017). Site and management history details are described in the original paper and only summarized herein:

The Goldsboro (coastal plain) research trial was conducted for 17 yr on a site where Wickham sandy loam (fine-loamy, mixed semiactive, thermic Typic Hapludults) was the predominant soil with inclusions of Tarboro loamy sand (mixed, thermic Typic Udipsamments). Agronomic treatments involved tillage practices and organic vs. conventional nutrient and pesticide management. The study was initiated in 1999 (Mueller et al., 2002) and included chemical no-till (NoTill) and conventional till (ConvTill) practices. A 3-yr rotation, which since 2006 included corn, sorghum-sudangrass (*Sorghum* × *drummondi)*, and double-crop soybean with winter wheat (*Triticum aestivum* L.) was followed. The original experimental design also included two organic treatments, both involving conventional tillage methods and adaptive cropping patterns. Since 2011, ConvTill-Org1 involved a 3-yr rotation with corn, soybean and a 1-yr stale seedbed with a sorghum-sudangrass cover crop. During the same time period ConvTill-Org2 involved a 3-yr rotation of corn, soybean, and sunflower (*Helianthus annuus* L.) with a rye (*Secale cereal* L.) cover crop before soybean, and a rye and legume cover crop mixture before corn and sunflower. The organic treatments utilized raw poultry litter as an external nutrient source, while the conventional plots received an equivalent N rate using commercial fertilizer sources. Yield measurements at this site were at times impacted by non-soil related factors, notably extreme weed and insect pressures in the organic treatments and asynchronous crop-years (Roper et al., 2017). They were therefore not considered for relating SH to crop yield.

The Reidsville (piedmont) research trial was conducted for 32 yr on soil mapped as Toast coarse sandy loam (fine, kaolinitic, mesic Typic Kanhapludults) and involved a multitude of tillage treatments. It was initiated in 1984 with nine tillage treatments and conventional chemical management that represented different levels of soil disturbance ranging from minimal to severe (Cassel et al., 1995; Meijer et al., 2013). The multitude of treatments and very subtle differences among some of them—coupled with high sampling variability—challenged statistical analyses so the nine treatments were consolidated into three groupings: (i) MinimumTill, combining no-till and in-row subsoiling in spring, (ii) ChiselTill combining chisel plowing in spring, chisel plowing in fall, chisel plowing and disking in spring, and chisel plowing and disking in fall, and (iii) MoldboardPlow, combining spring and fall moldboard plowing and disking. This experiment involved multiple years of crop yield measurements for both corn and soybean (Roper et al., 2017) that were used to identify relationships with SH indicators.

The Mills River (mountain) research trial was conducted for 22 yr on soil mapped as Delanco silt loam (fine-loamy, mixed, semiactive, mesic Aquic Hapludults). It was initiated in 1994 and designed as a 2×2 factorial with chisel and no-till practices being used with conventional and organic management. An additional chisel plus disk tillage treatment with no fertilizer or pesticide inputs was used as a control (Hoyt, 2005, 2007) but those results were not used for this study. As with the Goldsboro site, yield measurements from this experiment were impacted by non-soil related factors and complications related to crop sequences (Roper et al., 2017), and therefore were not considered for SH correlations with crop yield.

Soil Sampling

Soil samples were collected in late 2015 as discussed in Roper et al. (2017). Three sets of penetrometer measurements (Field Scout SC-900, Spectrum) to a depth of 45 cm were collected from each plot when the soil moisture content was approximately at field capacity. The highest resistance values within the 0-to-15- and 15-to-45-cm depths were recorded as SurfHard and SubHard values. Three to five auger cores were collected to a depth of 15 cm to obtain approximately 1400 cm^3 of soil from each plot. Due to plot-size limitations, this sampling protocol deviated from recommended CASH procedures which include more penetration measurements and a larger composite soil sample that is subsequently mixed and subsampled (Moebius-Clune et al., 2016). This procedural deviation likely increased sample variability and was the primary motivation to combine treatments into more generalized groupings for statistical analysis, as discussed above. After sampling, soil material was analyzed for multiple SH indicators at Cornell University (Schindelbeck et al., 2016).

Quantification of Soil Health Indicators

In addition to SurfHard and SubHard in-field measurements, a CASH analysis includes measurements for two other soil physical indicators (wet aggregate stability [AgStab], available water capacity [AWC]); four biological indicators (OM, ActC, autoclaved-citrate extractable protein [Protein], and soil respiration [Resp]) as well as seven soil chemical property indicators (pH and extractable P, K, Mg, Fe, Mn, and Zn). All analytical measurements were performed on disturbed, air-dried soil sieved to pass a 2-mm screen. Appropriate corrections for sample water content after air-drying were made after drying a subsample overnight at 105°C.

Detailed laboratory procedures are available from Schindelbeck et al. (2016). In short, AgStab was assessed using a rainfall simulator that generates 0.6 mm water drops and an adjustable Mariotte-type tube to control hydraulic pressure (Ogden et al., 1997). A single layer of aggregates was spread on a 0.25-mm mesh sieve that was placed 0.5 m below the rainfall simulator to thus apply 2.5 J of energy over a 300-s period. AgStab was determined as the fraction of soil remaining on the sieve after correcting for solid particles > 0.25-mm diam.

Soil AWC was determined as the difference between water content at field capacity (θ_{fc}) and permanent wilting point (θ_{pwp}) based on a gravimetric analysis (g water g $soil^{-1}$). Subsamples were saturated and equilibrated at −10 kPa (θ_{fc}) and −1500 kPa (θ_{pwp}) on ceramic high-pressure plates (Soil Moisture Equipment Corp.; Topp et al., 1993).

Soil OM content was determined by mass loss on ignition after 2 h in a 500°C muffle furnace. Active C was quantified by measuring absorbance with a handheld spectrophotometer (Hach)

Table 1. Means of comprehensive assessment of soil health (CASH) indicators for the coastal plain, piedmont and mountain sites, as well as the CASH database for Mid-Atlantic soils (from Fine et al., 2017).

Site	Region	*n*	Texture	AWC†	SurfHard	SubHard	Agstab	OM	Protein	Resp	ActC	pH	P	K	Mg	Fe	Mn	Zn
				m3/m3	–MPa–		%	%	mg/g	mgCO2/g	mg/kg		–mg/kg–					
Goldsboro	coastal plain	12	SL/LS	0.16	1.53	2.75	11	1.7	4.5	0.35	320	5.4	11.7	122	93	4.9	7.4	1.9
Reidsville	piedmont	32	SL	0.15	1.82	3.59	9	2.5	3.1	0.34	289	5.6	8.8	100	126	3.0	4.4	1.9
Mill River	mountain	20	SiL	0.21	1.48	2.61	12	2.6	4.0	0.39	312	5.6	6.3	123	151	4.2	6.6	0.8
database	Mid-Atlantic	101	coarse	0.11	1.25	2.21	45	2.2	6.4	0.52	335	6.0	14.2	92.5	87	3.5	7.4	1.9
database	Mid-Atlantic	317	medium	0.22	1.34	2.00	43	4.1	10.0	0.86	564	6.2	23.2	164	173	4.7	17.2	2.0

†AWC, available water capacity; SurfHard, penetration resistance within the 0- to 15-cm zone; SubHard, penetration resistance within the 15- to 45-cm zone; AgStab, water stable aggregation; OM, organic matter; Resp, respiration during a 4-d incubation; ActC, active carbon.

after oxidizing duplicate, 2.5-g soil samples with 20 mL of 0.02 M $KMnO_4$ solution (pH 7.2). This measurement is also referred to in the literature as permanganate oxidizable C, POXC.

Soil Resp was measured in duplicate after a 4-d incubation using a modified Haney and Haney (2010) method where soil was placed in a glass jar with a KOH-based CO_2 trap. The amount of CO_2 respired was determined by measuring the change in electrical conductivity of the solution with an OrionTM DuraProbeTM 4-Electrode Conductivity Cell (ThermoFisher Scientific, Inc.). The necessary background correction for atmospheric CO_2 was quantified using blank (i.e., no soil) incubations.

Protein content was measured by extracting a subsample with 0.02 M sodium citrate (pH 7), concentrating the sample through a series of centrifugation and autoclaving steps (Wright and Upadhyaya, 1996), and then quantifying soil protein content using a bicinchoninic acid assay with a bovine serum albumin standard curve.

Soil pH was measured in a 1:1 soil/water slurry. Plant available soil nutrient concentrations (P, K, Mg, Fe, Mn, and Zn) were measured using inductively coupled plasma optical emission spectrometry (SPECTRO Analytical Instruments Inc.) after extracting with a Modified Morgan solution (ammonium acetate plus acetic acid, pH 4.8; McIntosh, 1969). All nutrient contents were calculated per mass of soil (mg kg^{-1}).

Data Analysis

Pearson product-moment correlation coefficients were computed for every pair of SH indicators to create correlation matrices for the pooled dataset that included each individual trial, as well as all trials combined. Data for each trial were analyzed for significant treatment effects using analysis of variance and means separation with the Tukey post-hoc test for randomized complete block designs. Regression analysis was performed on corn and soybean yields vs. SH indicators for the Reidsville (piedmont) experiment, which contained 16 yr of continuous yield data (Roper et al., 2017). All statistical analyses and graphing were performed using RStudio software version 1.0.143 (R Core Team, 2016).

RESULTS AND DISCUSSION

Site Comparisons and Correlation Analysis

Soil health for each site was characterized by mean values (Table 1). The piedmont site (Reidsville) generally showed the least favorable values for physical and biological indicators, possibly because it only involved row crops and did not include any poultry litter additions or cover crop. The coastal plain (Goldsboro) site showed lower OM, but not commensurately lower Protein, ActC, and Resp, suggesting higher OM quality compared with the piedmont and mountain sites. That response was quite likely associated with the organic amendments and less organo-mineral bonds with coarser texture. The sites were strongly to moderately acidic (pH 5.4–5.6) but generally showed adequate levels of crop nutrients based on CASH interpretations (Moebius-Clune et al., 2016), confirming that the sites generally had good fertility management.

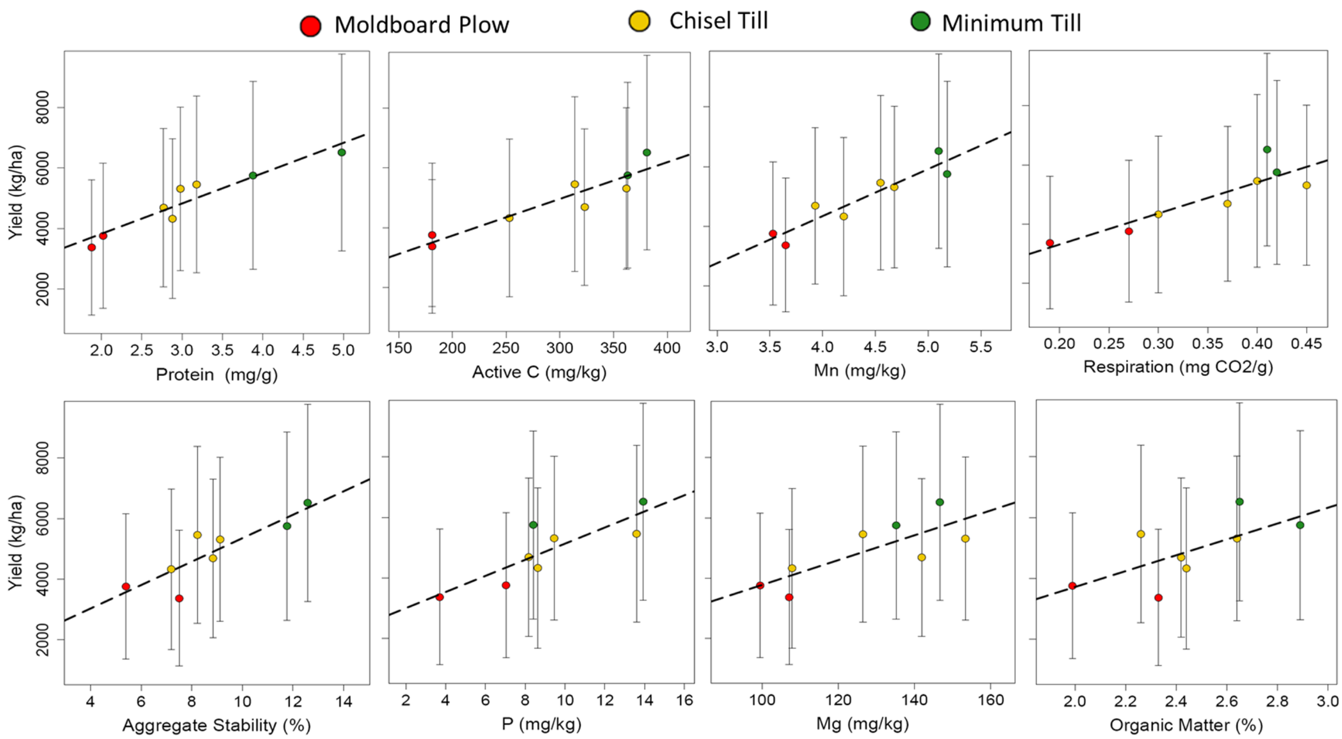

Fig. 1. Linear regression of corn yield on soil health indicators, organized from highest to lowest R^2 value (Table 7). Regression line is based on mean yields for tillage treatments, and error bars represent standard deviations associated with annual yield variability.

The SH indicators from each research site were compared with mean CASH database values for coarse and medium textured soils in the Mid-Atlantic (Table 1). Those reference data represent a diverse group of cropping systems and management practices within the region (Fine et al., 2017). Mean AgStab values for the NC research sites were well below the Mid-Atlantic equivalents for the same textural groups, and the biological indicators (OM, Protein, Resp, and ActC) were also below the Mid-Atlantic average. Those results suggest that the soils at the three research sites can be considered biologically and physically degraded, which is consistent with the generally low crop productivity. For example, corn grain yields averaged 6.21 and 4.89 Mg ha^{-1} (99 and 78 bu ac^{-1}) for the coastal plain and piedmont sites, which is well below the 3-yr (2013, 2015, and 2016) NC average of 8.03 Mg ha^{-1} (128 bu ac^{-1}; NASS, 2018). Soybean yields for the piedmont site averaged 2.94 Mg ha^{-1} (44 bu ac^{-1}) which was higher than the state average for the same 3-yr period (2.40 Mg ha^{-1} or 36 bu ac^{-1}), while fresh weight of sweetcorn averaged 12.7 Mg ha^{-1} (1134 cwt ac^{-1}) at the mountain site (Table 7 in Roper et al., 2017; Fig. 1, 2). In addition to generally low crop yields, interpretations in the previous analysis were based on CASH scores rather than measured values (Roper et al., 2017). This could be problematic since CASH scores are based on sigmoidal functions (Moebius-Clune et al., 2016) which show small rates of change at the low end of the curve, thereby diminishing differences in measured values from agronomic practices.

Pearson correlations among CASH indicators were developed for four cases: each of the three trials individually, and all trials combined (Tables 2–5). When SH data from all trials were pooled ($n = 64$), half (53) of the 105 possible correlations among SH indicators were significant at $\alpha = 0.05$ and a third (37) were significant at $\alpha = 0.01$. Significant correlations were more or less equally found among physical, biological, and chemical indicators, but the highest r-values tended to involve biological indicators or Mg. Soil OM generally showed only modest correlations with other biological indicators, suggesting some orthogonality (i.e., OM quantity and quality were somewhat independently expressed, e.g., the coastal plain soils tended to have higher Protein and ActC contents relative to OM). Among these indicators of labile OM, Protein, ActC, and Resp showed higher correlations, and were better correlated with AgStab than OM.

Less significant correlations were observed for individual sites, presumably due to a combination of less statistical power from a lower number of samples and smaller data ranges within individual sites. Correlation patterns for each site (Tables 3–5) also differed compared with the pooled data (Table 2), presumably reflecting treatment effects rather than soil type differences. Notably, individual research sites showed high correlations of AWC with OM, Mn, and Mg. Magnesium also correlated with other biological indicators and to a lesser extent physical indicators. Otherwise, chemical indicators showed limited intercorrelations. Overall, different correlations among SH indicator data from pooled and individual sites suggest variable impacts for dynamic soil properties related to agronomic management practices compared with inherent soil properties associated with the geographically separated trial sites and soil types (Table 2).

Treatment Effects

The three trials focused on different agronomic management practices, utilized different crop sequences, and were conducted

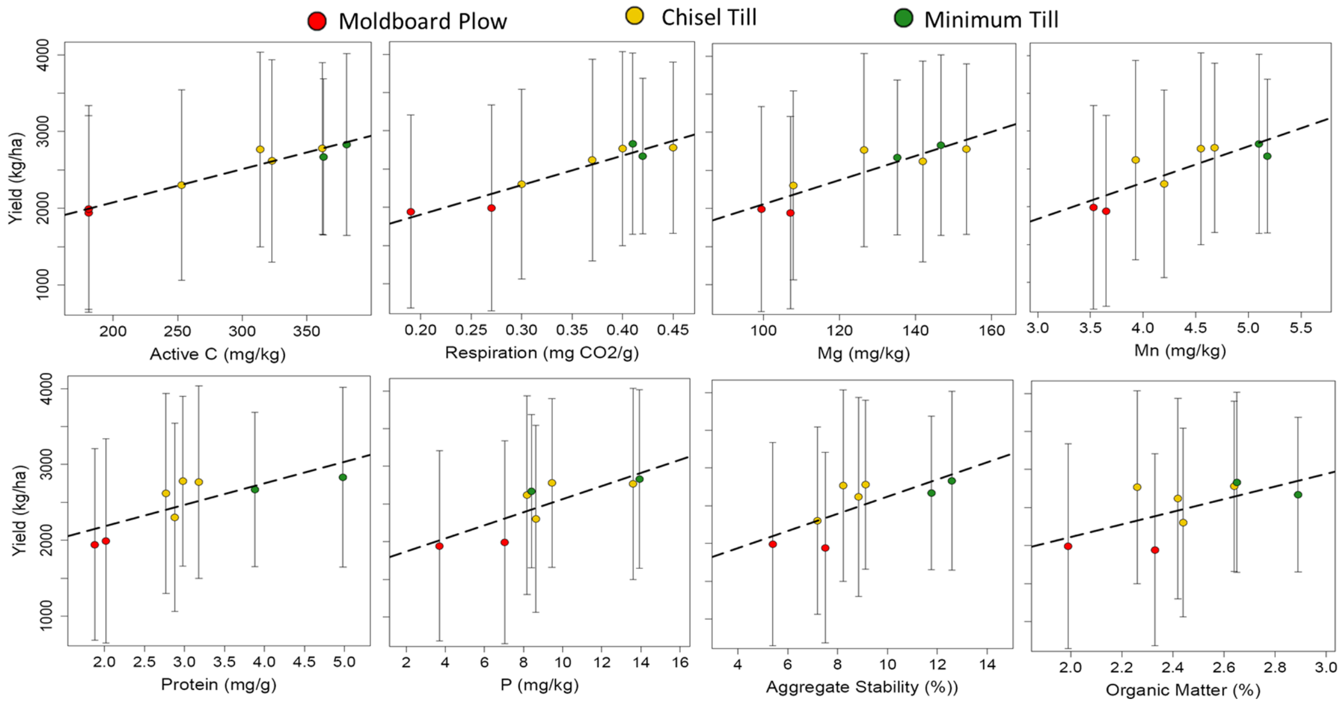

Fig. 2. Linear regression of soybean yield on soil health indicators, organized from highest to lowest R^2 value (Table 7). Regression line is based on mean yields for tillage treatments, and error bars represent standard deviations associated with annual yield variability.

in different regions of the state with dissimilar soils, all critical factors which were differentially expressed (Table 6). For example, treatment factors were generally less significant (α = 0.05) at the Goldsboro (coastal plain) site than at the Reidsville (piedmont) and Mills River (mountain) sites. Notably, the Reidsville site, which only involved tillage comparisons, showed more significant treatment effects than either site where different tillage practices were combined with conventional vs. organic management.

For all three sites, treatment effects were significantly expressed (α = 0.10) for ActC, Agstab, and P, and at two of three sites significant treatments were measured for Protein, pH, K, Mg, and Zn (Table 6). Other studies also found ActC and Agstab to be sensitive indicators, especially compared with OM, which often shows small nonsignificant effects from agronomic management practices (Idowu et al., 2009; Congreves et al., 2015; Kinoshita et al., 2017; Nunes et al., 2019).

For the Goldsboro (coastal plain) trial, average AgStab was significantly higher (α = 0.05) for No-Till than ConvTill-Org2, but for plant-available P NoTill was the lowest (Table 7). This suggests that the organic system with poultry litter additions benefited from soil nutrient additions, but had greater soil physical impediments because of tillage. The ActC also showed the highest numerical values for NoTill, but statistically they were not sufficient to be significant in a means comparison (α = 0.05).

The Reidsville (piedmont) trial involved a range of tillage practices that were pooled into three groups, MinimumTill, ChiselTill, and MoldboardPlow (Table 7). For most biological and physical SH indicators, tillage effects followed a consistent pattern of MinimumTill > ChiselTill > MoldboardPlow, which were significant (α = 0.05) for Agstab, Protein, Resp, and ActC. Tillage effects on chemical indicators were more variable, with only Mg and Mn showing the same pattern. Intensive tillage accelerates decomposition of plant biomass because of higher O_2 availability and exposure of older, physically protected soil organic C (Reicosky, 1997; Reicosky et al., 2011).

Tillage has thus been shown to increase CO_2 emissions (Melland et al., 2017), reduce surface SOM content (Kumar et al., 2017), and decrease the soil's ability to retain nutrients and maintain its physical quality (Martínez et al., 2016; Alhameid et al., 2017). Our results support the hypothesis that intensive tillage affects OM decomposition and impacts labile C and N fractions (Protein and ActC) more than total OM. Also, the Resp indicator shows higher decomposition rates for reduced tillage soil after it is disturbed by sample processing, suggesting that the labile organic material is better retained when left undisturbed. Low OM was also associated with decreased AgStab, an important indicator of physical soil quality. In a study with NC and Virginia soils, Franzluebbers (2018) and Franzluebbers et al. (2018a, 2018b) conclude that the assessment of readily-decomposed C and N through the Resp test is a better predictor of plant N availability than total N and can be used to optimize supplemental N fertilizer rates. Yost et al. (2018) also found that Resp explained some of the variability in corn N response in eight Midwest states.

The Mills River (mountain) trial involved a factorial experiment that we analyzed to contrast organic vs. conventional and NoTill vs. ChiselTill (Table 7). Organic treatments focused on the use of cover crops and poultry litter, two practices that generally resulted in more favorable physical and biological indicator values than conventional treatments, but the only significant (α = 0.05) difference was for ActC and there were no significant interaction effects. Many chemical indicators had higher values with organic management, suggesting that effective nutri-

Table 2. Pearson correlations among comprehensive assessment of soil health (CASH) indicators for all coastal plain, piedmont and mountain samples with $p < 0.05$ (underlined numbers $p < 0.01$; $n = 64$).

	AWC†	Surf Hard	Sub Hard	Ag Stab	OM	Protein	Resp	ActC	pH	P	K	Mg	Fe	Mn	Zn
AWC	1.00														
SurfHard		1.00													
SubHard	–0.59	0.37	1.00												
AgStab	0.28		–0.28												
OM	0.47			0.25	1.00										
Protein	0.35		–0.55	0.55		1.00									
Resp	0.31	–0.30	–0.34	0.28	0.41	0.48	1.00								
ActC	0.25		–0.30	0.56	0.39	0.67	0.73	1.00							
pH							0.59	0.37	1.00						
P	–0.37				–0.37	0.50	0.27	0.37		1.00					
K	0.38	–0.28	–0.34		0.29	0.31	0.52	0.47	0.36		1.00				
Mg	0.53		–0.26	0.30	0.78		0.64	0.59	0.52		0.60	1.00			
Fe								–0.24	–0.36			–0.41	1.00		
Mn	0.57		–0.52	0.25		0.43	0.30	0.24			0.35			1.00	
Zn	–0.41									0.42		–0.27			1.00

†AWC, available water capacity; SurfHard, penetration resistance within the 0 to 15-cm zone; SubHard, penetration resistance within the 15- to 45-cm zone; AgStab, water stable aggregation; OM, organic matter; Resp, respiration during a 4-d incubation; ActC, active carbon.

ent additions through poultry litter likely exceeded those from inorganic fertilizer. Except for surface penetration resistance (SurfHard), NoTill practices consistently showed more favorable physical and biological SH indicator values than ChiselTill, with significant differences ($\alpha = 0.05$) for AggStab, Protein, P and Zn. The Mills River experiment thus suggests that tillage and organic vs. conventional treatment effects are differentially expressed through SH indicators.

This re-analysis of the NC data counters previous interpretations (Roper et al., 2017) and is consistent with results from New York trials involving tillage practices, crop rotations, and cover crop treatments that showed CASH indicators could differentiate among various management practices (Nunes et al., 2019). In these trials, ActC, Protein, Resp, AgStab, and SurfHard showed significant responses to tillage (no-till, conventional till), and AWC to cover cropping. Similarly, Congreves et al. (2015) measured significant responses of CASH indicators (AgStab, pH and Zn) to tillage treatments (no-till, conventional till) in an Ontario study. AgStab, P, and Mn also responded to crop rotation effects. Furthermore, an assessment of a long-term tillage (plow, no-till) and crop residue management (removed or retained) study by Kinoshita et al. (2017) showed that 40-yr effects were discernable in the 0- to 15-cm layer for all measured biological indicators and the majority of physical (notably AgStab) and chemical indicators. Effects in some cases were also detected within the subsoil. In 10 European long-term experiments involving tillage and organic input management, ActC (POXC) was determined to be the most sensitive and useful indicator for labile C (Bünemann et al., 2018; Bongiorno et al., 2019). Collectively, these reports are in agreement with our re-

Table 3. Pearson correlations among correlations among comprehensive assessment of soil health (CASH) indicators for coastal plain (Goldsboro) samples with $p < 0.05$ (underlined numbers $p < 0.01$; $n = 12$).

	AWC†	Surf Hard	Sub Hard	Ag Stab	OM	Protein	Resp	ActC	pH	P	K	Mg	Fe	Mn	Zn
AWC	1.00														
SurfHard		1.00													
SubHard	–0.61	0.65	1.00												
AgStab		0.61		1.00											
OM	0.87	–0.57	–0.62		1.00										
Protein						1.00									
Resp	0.67	–0.59			0.77		1.00								
ActC						0.61		1.00							
pH	–0.63						0.70	0.62	1.00						
P										1.00					
K		–0.63		–0.79	0.75		0.81		0.70		1.00				
Mg	0.76	–0.59	–0.62		0.93		0.79		0.62		0.79	1.00			
Fe													1.00		
Mn	0.84				0.66					–0.64				1.00	
Zn										0.70					1.00

†AWC, available water capacity; SurfHard, penetration resistance within the 0- to 15-cm zone; SubHard, penetration resistance within the 15- to 45-cm zone; AgStab, water stable aggregation; OM, organic matter; Resp, respiration during a 4-d incubation; ActC, active carbon.

Table 4. Pearson correlations among correlations among comprehensive assessment of soil health (CASH) indicators for all piedmont (Reidsville) samples with $p < 0.05$ (underlined numbers $p < 0.01$; $n = 32$).

	AWC†	Surf Hard	Sub Hard	Ag Stab	OM	Protein	Resp	ActC	pH	P	K	Mg	Fe	Mn	Zn
AWC	1.00														
SurfHard		1.00													
SubHard			.00												
AgStab				1.00											
OM	0.68			0.59	1.00										
Protein			–0.44	0.47		1.00									
Resp				0.47	0.37	0.65									
ActC	0.40			0.67	0.58	0.73	0.84	1.00							
pH							0.60	0.40	1.00						
P						0.67	0.50	0.40		1.00					
K							0.49	0.46	0.47		1.00				
Mg	0.41			0.69	0.75	0.40	0.69	0.80	0.47		0.55				
Fe					–0.51					0.38		–0.52	1.00		
Mn				0.53	0.49	0.47	0.42	0.51						1.00	
Zn			–0.35								–0.40			0.59	1.00

†AWC, available water capacity; SurfHard, penetration resistance within the 0- to 15-cm zone; SubHard, penetration resistance within the 15- to 45-cm zone; AgStab, water stable aggregation; OM, organic matter; Resp, respiration during a 4-d incubation; ActC, active carbon.

sults showing that CASH indicators can differentiate agronomic management effects.

Soil Health and Yield

Demonstrating positive relationships between SH and crop yield is of great interest to farmers as it could justify management investments in practices such as reduced tillage, adding organic inputs, or altering rotations. But this has been difficult, especially in experimental trials due to often inconsistent yield data or confounding impacts (e.g., pest pressure, weather variability, and/or extraneous management factors). Roper et al. (2017; Fig. 2 therein) used the NC dataset to determine relationships between overall SH scores and crop yield for the piedmont and mountain sites but found no correlation. We hypothesize that this was primarily because of the use of overall SH scores (masking individual indicator effects) and confounding impacts associated with non-soil factors (notably pest pressures). Nevertheless, the Reidsville (piedmont) site provided an excellent experimental dataset to evaluate correlations between individual CASH indicators (rather than scores) and yield, because (i) data were available from 17 corn harvests (between 1987 and 2015) and 10 soybean harvests (1990 to 2014), (ii) there was a gradient of tillage intensities, and (iii) there were no apparent confounding factors affecting crop yields at this site (as opposed to the coastal plain and mountain experiments).

Linear regression line plots showing relationships between various SH indicators and yields of corn (Fig. 1) and soybean (Fig. 2) had high annual variability as expressed by standard deviation (sd) bars (pooled values of 2.72 and 1.21 Mg ha^{-1} for corn and soybean, respectively). Corn yields were <7 Mg ha^{-1} (112 bu ac^{-1}) with about half of the means. Multi-year mean

Table 5. Pearson correlations among correlations among comprehensive assessment of soil health (CASH) indicators for mountain (Mills River) samples with $p < 0.05$ (underlined numbers $p < 0.01$; $n = 20$).

	AWC†	Surf Hard	Sub Hard	Ag Stab	OM	Protein	Resp	ActC	pH	P	K	Mg	Fe	Mn	Zn
AWC	1.00														
SurfHard		1.00													
SubHard															
AgStab															
OM	0.65														
Protein	0.53			0.67	0.62	1.00									
Resp					0.46		1.00								
ActC				0.61		0.73	0.67	1.00							
pH							0.60	0.45	1.00						
P				0.46	0.47	0.70		0.78		1.00					
K					0.52	0.47	0.47	0.65		0.50	1.00				
Mg			–0.45			0.48	0.64	0.81	0.56	0.49	0.83	1.00			
Fe								–0.46	–0.50			–0.48	1.00		
Mn													–0.47	1.00	
Zn				0.66		0.68		0.60		0.73					1.00

†AWC, available water capacity; SurfHard, penetration resistance within the 0- to 15-cm zone; SubHard, penetration resistance within the 15- to 45-cm zone; AgStab, water stable aggregation; OM, organic matter; Resp, respiration during a 4-d incubation; ActC, active carbon.

Table 6. P values for treatment effects on correlations among comprehensive assessment of soil health (CASH) indicators for Goldsboro, Reidsville, and Mills River samples.

	AWC†	Surf Hard	Sub Hard	Agg Stab	OM	Protein	Resp	ActC	pH	P	K	Mg	Fe	Mn	Zn
Goldsboro	NS‡	NS	NS	0.020	NS	NS	NS	0.072	NS	0.035	NS	NS	NS	NS	0.046
Reidsville	NS	NS	NS	0.006	NS	0.002	0.001	< 0.001	0.01	0.06	0.008	0.016	NS	0.002	NS
Mills River	NS	NS	NS	0.052	NS	0.002	NS	< 0.001	0.014	< 0.001	0.002	0.011	0.075	NS	< 0.001

†AWC, available water capacity; SurfHard, penetration resistance within the 0- to 15-cm zone; SubHard, penetration resistance within the 15- to 45-cm zone; AgStab, water stable aggregation; OM, organic matter; Resp, respiration during a 4-d incubation; ActC, active carbon.

‡NS: not significant at $\alpha = 0.1$.

yield values, however, were often closely correlated with SH indicators, especially for the biological properties and processes (Fig. 1 and 2). Eight SH indicators (Agstab, OM, Protein, Resp, ActC, P, Mg and Mn) showed significant ($\alpha = 0.10$) linear regression effects with mean corn and soybean yields (Table 8). This implies that tillage-related SH differences as indicated by the SH values can on average be expected to result in higher crop yields. For each SH indicator the linear relationship with mean corn and soybean yield generally followed the pattern MinimumTill > ChiselTill > MoldboardPlow, especially for the biological measurements (Fig. 1, 2). This implies that reduced tillage resulted in better SH indicator values that in turn were associated with higher average crop yields. This experiment thus provides some of the very best-available results linking agronomic management practices to both SH and yield benefits, and counters conclusions by Roper et al. (2017) that SH indicators could not be correlated to crop yield, which is relevant to commercial farmers.

For corn yields, the highest significant regression coefficients and associated R^2_{adj} values (Table 8) followed the order of Protein > ActC > Mn > Resp > Aggstab > *P* > Mg > OM, while for soybean yield they were ActC > Resp > Mg > Mn > Protein > *P* > Aggstab > OM (Fig. 1, 2; note: X-Y plots are ordered by R^2_{adj} value). Several insightful conclusions can be drawn from this re-analysis:

1. Biological indicators associated with labile C and N show the strongest linear regression fit with mean yield for both crops: ActC had very high R^2_{adj} values of 0.93 and 0.85 for mean soybean and corn yields, respectively, and Resp shows R^2_{adj} values of 0.90 for mean soybean yield and 0.75 for corn. Protein values showed the highest fit with mean corn yield ($R^2_{adj} = 0.88$), but a lower correlation with soybean yield (0.55), suggesting that a legume crop would benefit less from high soil Protein levels–and presumably the associated organic N–than a non-legume crop. This makes biological sense.
2. Soil OM levels showed relatively weak regression fits with mean yield (ranked eighth for both corn and soybean; $p = 0.06$ and 0.09, respectively), while OM quality indicators (i.e., Protein, ActC) correlated much better, suggesting that OM quality may be more relevant to crop yield than OM quantity.
3. Strong regression fits between crop yield and biological indicators suggest that the negative impacts of intensive

Table 7. Soil management contrasts related to correlations among comprehensive assessment of soil health (CASH) indicators for Goldsboro, Reidsville, and Mills River samples. Underlined numbers indicate treatment effects at $\alpha = 0.05$. Of those, treatments within the same site followed by the same letter are not significantly different.

Site	AWC†	Surf Hard	Sub Hard	Agg Stab	OM	Protein	Resp	ActC	pH	P	K	Mg	Fe	Mn	Zn
Goldsboro															
ConvTill	0.160	1.72	2.877	13.07a	1.433	4.37	0.287	277	5.00	9.37ab	93.1	57.0	4.57	9.03	1.30
ConvTill-Org1	0.147	1.45	3.023	9.83ab	1.433	4.33	0.400	304	5.57	17.10a	122.3	77.3	5.97	5.80	2.93
ConvTill-Org2	0.167	1.15	2.563	6.60b	1.933	4.23	0.383	294	5.57	12.13ab	161.9	128.0	2.80	7.70	2.10
NoTill	0.183	1.78	2.520	14.40a	1.833	5.00	0.347	406	5.37	8.00b	108.9	111.0	6.10	7.13	1.30
p-value	0.707	0.584	0.768	0.020	0.589	0.110	0.426	0.072	0.183	0.035	0.118	0.396	0.479	0.720	0.046
Reidsville															
MoldboardPlow	0.149	2.00	3.75	6.45b	2.16	1.95c	0.229b	181b	5.39b	5.36	83.8b	103.3b	2.78	3.59b	1.663
ChiselTill	0.149	1.61	3.71	8.34b	2.44	2.95b	0.379a	313a	5.77a	9.96	116.4a	132.4ab	3.16	4.34b	1.450
MinimumTill	0.160	1.84	3.30	12.17a	2.77	4.43a	0.414a	372a	5.53ab	11.16	100.1ab	141.0a	3.00	5.14a	2.438
p-value	0.233	0.206	0.333	0.006	0.139	< 0.001	0.001	< 0.001	0.011	0.066	0.007	0.016	0.894	0.002	0.129
Mills River															
Conventional	0.207	1.655	2.760	11.73	2.532	3.79	0.375	277b	5.55	4.79b	90.9b	133.2b	5.34a	6.17	0.793
Organic	0.212	1.455	2.471	13.68	2.660	4.36	0.424	387a	5.78	9.22a	160.0a	179.1a	2.24b	7.09	0.950
p-value	0.428	0.474	0.080	0.572	0.582	0.233	0.317	0.003	0.139	0.011	< 0.001	< 0.001	0.039	0.252	0.210
ChiselTill	0.209	1.405	2.606	8.38b	2.481	3.40b	0.391	296	5.78	4.84b	124.4	153.1	3.98	6.29	0.588b
NoTill	0.211	1.705	2.625	17.03a	2.711	4.76a	0.408	367	5.56	9.18a	126.6	159.2	3.60	6.97	1.075a
p-value	0.694	0.277	0.914	0.003	0.314	< 0.001	0.743	0.085	0.168	0.013	0.918	0.704	0.817	0.393	0.004

†AWC, available water capacity; SurfHard, penetration resistance within the 0- to 15-cm zone; SubHard, penetration resistance within the 15- to 45-cm zone; AgStab, water stable aggregation; OM, organic matter; Resp, respiration during a 4-d incubation; ActC, active carbon.

Table 8. Results for linear regression of mean corn and soybean yields on correlations among comprehensive assessment of soil health (CASH) indicators, Reidsville site (all $p < 0.05$; underlined: $R^2_{adj} > 0.75$). SD is the pooled standard deviation associated with annual yield variability.

	AggStab†	OM	Protein	Resp	ActC	P	Mg	Mn
	%	%	mg g^{-1}	mg CO2 g^{-1}		–mg kg^{-1}–		
				Corn Yield				
R^2_{adj}	0.71	0.37	0.88	0.75	0.85	0.66	0.56	0.85
p-value, regr coeff	0.005	0.063	< 0.001	0.003	< 0.001	0.008	0.019	< 0.001
intercept	1487	–1492	1822	1219	1284	2475	–333	–1946
slope	386	2606	1002	10478	12.26	266	41.1	1572
				Soybean Yield				
R^2_{adj}	0.48	0.31	0.55	0.90	0.93	0.59	0.76	0.65
p-value, regr coeff	0.033	0.090	0.021	< 0.001	< 0.001	0.015	0.003	0.01
intercept	1483	447	1616	1132	1207	1695	469	400
slope	113	831	283	3855	4.34	87	15.8	479

† AgStab, water stable aggregation; OM, organic matter; Resp, respiration during a 4-d incubation; ActC, active carbon.

tillage on labile organic C fractions that are most readily decomposed also adversely affect crop yield. Notably, Protein represents low C/N OM that is readily used as a microbial food source and ActC mimics OM decomposition including more recalcitrant forms (Weil et al., 2003; Romero et al., 2018).

4. Manganese is strongly impacted by tillage intensity, which in turn correlates well with mean corn and soybean yield ($R^2_{adj} = 0.85$ and 0.65, respectively). Unlike other crop nutrients, Mn was not managed through external applications and Mn contents for this experiment were not out of line with regional averages (Table 1). Recent studies have shown that Mn redox cycling is important in OM decomposition (Keiluweit, 2015), which according to these results is impacted by tillage intensity.
5. AgStab is negatively impacted by tillage intensity and shows modest correlations with yield, presumably due to aggregation effects from higher biological activity (Magdoff and van Es, 2009), as evidenced by the biological SH indicators (Table 8).
6. Weaker correlations were observed for P and Mg (Fig. 1 and 2), which presumably relates to their enhanced availability with higher OM quality.

CONCLUSIONS

This study re-analyzed data from three long-term agronomic experiments in NC and conveys different perspectives from the paper by Roper et al. (2017), which had concluded that the CASH framework and two other soil tests have limited ability to discern among management practices. It had also concluded that there was a lack of correlation between SH measurements and crop yield. Our analysis utilizes more nuanced interpretations and is mostly in disagreement with those conclusions, but corroborates other previous research on the utility of SH indicators. This is in part because of the fact that the Roper et al. (2017) analysis was negatively impacted by low statistical power from high sample variability, interpretations based on nonlinear scoring functions that obscured effects of individual treatments, as well as insufficient differentiation of the performance of CASH from other soil tests (i.e., NSHT and NCDACS). Moreover, their inference that overall SH scores and crop yields were not correlated was strongly confounded by several non-soil factors (i.e., very low crop yields in some years, and pest pressures related to organic practices). Furthermore, the analyses considered SH scores rather than individual indicator values, which was problematic because of the overall low quality of the soils.

Our analysis provides a different perspective and concludes that multi-functional SH indicators (biological, physical, chemical) indeed offer valuable insights for interpreting long-term effects of agronomic management practices. Notably, we demonstrated that different management practices variably impact different aspects of SH, especially indicators associated with labile OM (ActC, Protein, Resp, AgStab). Changes in tillage intensity appear to have greater impacts than organic vs. conventional practices. Also, correlations among SH indicators varied based on the geographic scope of the analysis and whether it involved a single-location trial or multiple trials.

Furthermore, the piedmont trial involving a range of tillage intensities and 16-yr cropping data offered unique insights into correlations between SH indicators and crop yields as impacted by tillage. Although annual variability of corn and soybean yields was high, the long-term average yields showed very good linear regression fits with SH indicators related to OM quality. This suggests that labile sources of C and N are important to SH and crop performance. Results also show that Mn, which plays a role in OM dynamics, is impacted by tillage practices and in turn correlates with yields.

Overall we conclude that, contrary to previous inferences from these trials, (i) comprehensive SH assessment through the CASH framework was able to discern effects of agronomic management practices (tillage, organic practices), (ii) biological indicators associated with labile C and N are most impacted by management practices, especially tillage, and (iii) SH indicators can be related to yield of corn and soybean under varying tillage intensities, but scoring curves for SH may need to be regionalized.

ACKNOWLEDGMENTS

The authors acknowledge the experimental work, data and funding associated with the original paper by Roper et al., 2017.

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