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Soil quality is a critical link between land management and water quality. We aimed to assess soil quality within the Cedar Creek Watershed, a pothole-dominated subwatershed within the St. Joseph River watershed that drains into the Western Lake Erie Basin in northeastern Indiana. The Soil Management Assessment Framework (SMAF) with 10 soil quality indicators was used to assess inherent and dynamic soil and environmental characteristics across crop rotations, tillage practices, and landscape positions. Surface physical, chemical, and nutrient component indices were high, averaging 90, 93, and 98% of the optimum, respectively. Surface biology had the lowest component score, averaging 69% of the optimum. Crop rotation, tillage, and landscape position effects were assessed using ANOVA. Crop selection had a greater impact on soil quality than tillage, with perennial grass systems having higher values than corn (*Zea mays* L.) or soybean [*Glycine max* (L.) Merr.]. Furthermore, soybean rotations often scored higher than corn rotations. Uncultivated perennial grass systems had higher overall soil quality index (SQI) values and physical, chemical, and biological component values than no-till or chisel–disk systems. Chisel–disk effects on overall and component SQI values were generally not significantly different from no-till management except for a few physical indicators. Toe-slopes had higher physical, biological, and overall SQI values than summit positions but toe-slope values were not significantly different from those of mid-slope positions. This work highlights the positive effects of perennial grass systems, the negative effects of corn-based systems, and the neutral effects of tillage on soil quality.

Abbreviations: BG, β-glucosidase; C-A-A, corn–alfalfa–alfalfa rotation; C-S, corn–soybean rotation; C-S-W, corn–soybean–winter wheat rotation; C_{min}, potentially mineralizable C; CEAP, Conservation Effects Assessment Project; C-D, fall chisel–spring disk tillage system; ρ_b, bulk density; EC, electrical conductivity; MAS, macroaggregate stability; MBC, microbial biomass C; N_{min}, potentially mineralizable N; PG, perennial grasses rotation; SMAF, Soil Management Assessment Framework; SOC, soil organic C; SQI, soil quality index; S-S-S, 3-yr soybean rotation; S-S-W, soybean–soybean–wheat rotation.

Core Ideas

- **Soil quality scores were highest in perennial grass systems, followed by a soybean-dominated rotation, followed by a corn-based rotation.**
- **No-till crop production had no higher soil quality score than chisel–disk tillage but the uncultivated perennial grass system scored higher than both.**
- **In this crop production-dominated region, soil quality is driven by biological properties like soil C and β-glucosidase activity and physical properties like bulk density and macroaggregate stability.**

Soil quality, or soil health, is considered a critical link between land management and the quality of adjacent water bodies (National Research Council, 1993) and is often positively correlated with grain yield (Nakajima et al., 2016). The conservation effects assessment project (CEAP) was initiated by the USDA-NRCS in 2003 to provide a scientific basis for assessing the effects of land management practices on water quality (Richardson et al., 2008). In 2006, linking conservation practices and water quality to soil quality became a priority for the CEAP (Stott et al., 2011). Within the USDA-ARS CEAP project, there are 17 cropland experimental watersheds where relationships among conservation practices, soil quality and water quality are being quantified (USDA-ARS, 2016).

One ARS cropland CEAP watershed is located within the St. Joseph River watershed, a major contributor to the Great Lakes Western Lake Erie Basin. The watershed covers 280,852 ha, with 56% lying in northeast Indiana, 22% in

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northwest Ohio, and 22% in south central Michigan. Land use is comprised of 89% agriculture, woodland, or wetland and the remaining 11% is commercial or residential. For this study, we concentrated on areas along Cedar Creek, the largest tributary to the St. Joseph River. The Cedar Creek subwatershed covers 25% of the St. Joseph River watershed, draining about 70, 700 ha in DeKalb, Allen, and Noble counties of Indiana (Smiley et al., 2009; Zuercher et al., 2011).

Soil quality, a site-specific characteristic, is impacted by both inherent and dynamic factors including climate, soil type, and management decisions such as crop selection and tillage practices. Cropland soil quality is also influenced by a variety of factors including the environment, inherent soil characteristics, and human values such as intended land use, management goals, and environmental protection priorities. For this study, the SMAF (Andrews et al., 2004), which has been used in several U.S. and international locations to evaluate management impacts on near-surface, (0–5 cm and 5–15 cm) soil properties (Cambardella et al., 2004; Erkossa et al., 2007; Fernández-Ugalde et al., 2009; Imaz et al., 2010; Jokela et al., 2011; Karlen et al., 2013; Liebig et al., 2012; Ozgoz et al., 2013; Stott et al., 2011, 2013) was selected as the assessment tool. Besides SMAF, there are other soil quality assessment tools available (Stott et al., 2010), including the AgroEcosystem Performance Assessment Tool (Liebig et al., 2004) and the Soil Conditioning Index (USDA-NRCS, 2002). There is general agreement between the AgroEcosystem Performance Assessment Tool and the SMAF (Wienhold et al., 2006) but since the two tools differ in their intended uses and input requirements, a true comparison is difficult. The Soil Conditioning Index estimates trends in soil organic C (SOC) content, and when the Soil Conditioning Index was compared with the SMAF–SOC indicator scores, the SMAF–SOC was more successful in separating different cropping systems imposed on semiarid, hot, sandy soils within the Southern High Plains of western Texas (Zobeck et al., 2007).

The SMAF uses soil taxonomy as a foundation for overall soil quality assessments and cumulative indices. It also allows for modification of scoring functions based on soil suborder characteristics. Other factors, such as climate, inherent soil properties, slope, and crop at the time of sampling are also taken into account, thus providing a comparative basis for indicator interpretation (Andrews et al., 2004; Stott et al., 2010; Wienhold et al., 2009). The SMAF includes soil physical, chemical, and biological indicators that are dynamic and sensitive to changes in management.

Previous work has connected soil quality indicators to crop rotation, tillage, and landscape positions. In some regions, crop rotation has had minimal effects on soil quality indicators and soil quality appears to be dominated by fertilizer input, tillage, and inherent soil properties (Campbell et al., 1991; Liebig et al., 2002; Sharma et al., 2005). Tillage and crop residue management have long been reported to have an effect on soil quality indicators, representing physical [e.g. erodibility, aggregate stability, bulk density (ρ_b), and hydraulic conductivity], chemical (e.g. pH and nutrients), and biological (e.g. microbial biomass, mycorrhiza, and macrofauna) properties and processes (Kumar and Goh, 2000; Silgram and Shepherd, 1999). From a soil productivity perspective, Kravchenko and Bullock (2000) found that landscape position accounted for 20% of the variability in corn and soybean yields in Indiana and Illinois. Furthermore, Cavigelli et al. (2005) found that numerous indicators of microbial activity, population, and community structure varied by soil type. Although throughout the past few decades several research studies have been dedicated to determining the effects of management and inherent soil properties on what are now deemed soil quality indicators, the effects of soil and crop management as well as inherent soil properties have not been clearly translated to SQI values.

Our objectives are to quantify the effects of crop rotation, tillage practice, and landscape position on near-surface SQI values within the Cedar Creek watershed. Since this is an observational study, we are limited in our ability to make statistical inferences, although the length of time under various management scenarios can provide insight regarding which management practices are associated with changes in soil quality indicators and thus SQI values.

MATERIALS AND METHODS

Watershed Characteristics

Cedar Creek is located in northeastern Indiana (Fig. 1), lying mostly within DeKalb County (41°53'78"–41°19'23" N, 85°31'88"–84°91'50" W). The watershed is mostly agriculture with 64% cropland, dominated by corn and soybean; 15% pasture or forage; 10% woodland or wetland; and 11% in urban, farmstead, rural residential, golf course, airport, commercial, or similar uses (Zuercher et al., 2011). The landscape is generally flat to gently rolling, with morainal hills composed of glacial till or sand and gravel, a local relief ranging from 30 to 60 m, and many fields dominated by pothole topography (i.e., closed depressions located throughout the catchment that hold water after large rainfall events) (Smiley et al., 2009; Smith et al., 2008). Landscape summits are often highly eroded and depressions contain depositional material because the landscape is not dendritic in this area. The Cedar Creek watershed has a minimum and maximum elevation of 238 and 326 m above sea level, respectively, with the lowest point located in Allen County near the confluence of Cedar Creek and the St. Joseph River. Soils are typically classified as Alfisols or Mollisols derived from glacial till. The climate is temperate humid, with a 30-yr average annual rainfall and temperature of 940 mm and 9.9° C, respectively.

Field Site and Soil Sampling

Sampling locations and the corresponding management information are summarized in Table 1. Field sites were farms selected on the basis of the inclusion of pothole topography and to provide a variety of tillage and cropping systems. Crop rotations were in place for a minimum of 10 yr at each field site. Plant nutrients were primarily applied as inorganic fertilizers and farmers and cooperators were encouraged to follow regional fertility guidelines (Vitosh et al., 1995). The area has few sources of animal manure and less than 5% of cropland in the watershed receives manure, which is typically applied on a crop N need basis (Smith et al., 2008). Soil samples were collected after harvest in November 2007 from 20 sites. Transects were laid out along the toposequence, bisecting potholes with two transects per pothole and six sampling locations per transect (two each at summit, mid-, and toe-slope positions) for a total of 12 sampling locations per site. Surface residue was cleared from each sampling location, so all samples started at the soil surface. Soil cores were collected to a depth of 15 cm using a 3.2-cm diameter soil probe and separated into 0- to 5-cm and 5- to 15-cm depth increments. For each landscape position and depth, soil cores were composited and placed in plastic bags, sealed, and held in coolers until they could be analyzed. Physical and some biological analyses were conducted at the USDA-ARS National Soil Erosion Research Laboratory. The remainder of the biological analy-

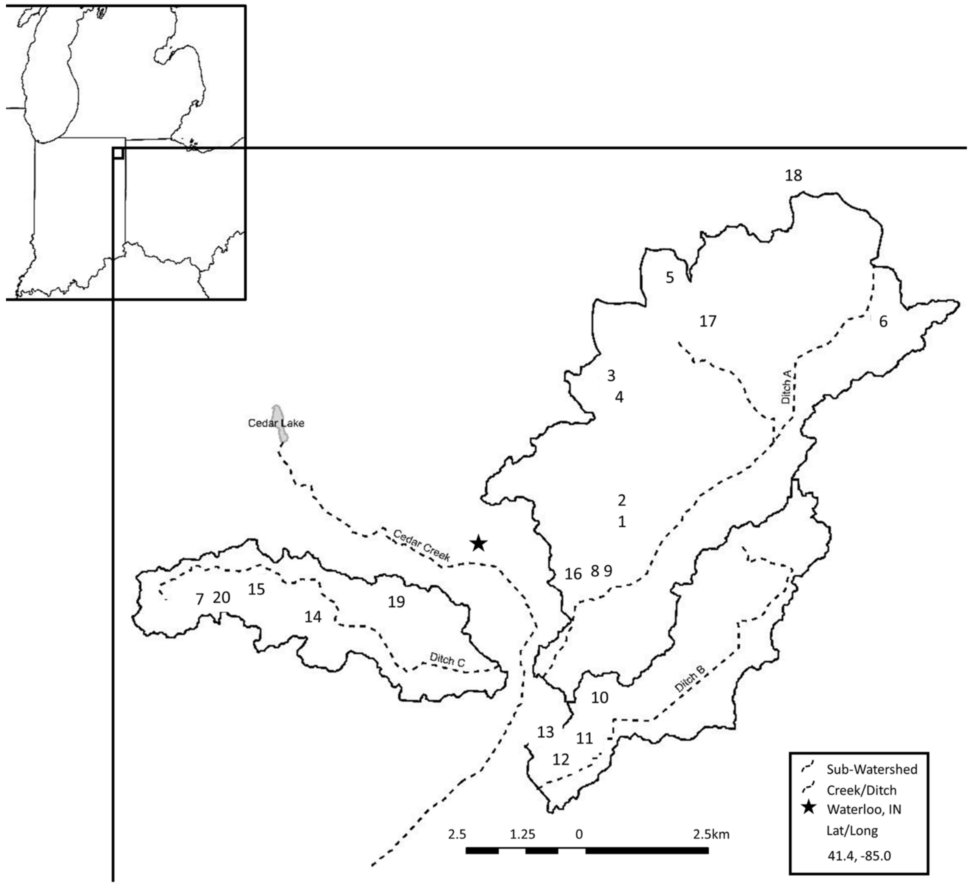

Figure 1. The study area in the upper Cedar Creek watershed located near Waterloo, IN, USA (41.43 N, 85.02 W) drains into three ditches (A, B, and C). Field site numbers correspond to those in Table 1.

Table 1. Description of watershed study sites, including the crop at the time of sampling, crop rotation, tillage management, and soil series.

Field site†	2007 crop	Crop rotation	Tillage	Soil series‡	Notes
1	Corn	C-S-W	NT	Blount	
2	Corn	C-S-W	NT	Blount, Pewamo	
3	Alfalfa	C-A-A	C-D	Glynwood, Morley, Wallkill	Manure applied prior to sampling
4	Soybean	C-S-W	C-D	Glynwood, Morley, Wallkill	
5	Wheat	C-S-W	NT	Blount, Pewamo	
6	Soybean	C-S-W	NT	Pewamo, Oshtemo	*Trifolium pretense* cover crop
7	Wheat	C-S-W	C-D	Glynwood, Wallkill	
8	Soybean	S-S-S	C-D	Blount, Pewamo	
9	Soybean	S-S-W	C-D	Blount	
10	Wheat	C-S-W	NT	Blount, Pewamo	
11	Corn	C-S	NT	Pewamo, Houghton	
12	Soybean	C-S	NT	Blount, Pewamo	
13	Corn	C-S-W	NT	Blount, Pewamo	
14	Corn	C-S	C-D	Pewamo, Glynwood	
15	Soybean	C-S	NT	Pewamo, Glynwood	Lime applied prior to sampling
16	Corn	C-S	NT	Blount, Pewamo, Glynwood	
17	Wheat	C-S-W	C-D	Rawson, Wallkill, Glynwood	
18	CRP	PG	–	Pewamo, Glynwood, Rawson	
19	CRP	PG	–	Blount, Pewamo, Glynwood	
20	Soybean	C-S-W	C-D	Blount, Pewamo	Manure applied regularly

† Field site ID numbers correspond to the locations in Fig. 1.

‡ See Table 2 for soil series descriptions.

§ C-S-W, corn–soybean–wheat; C-A-A, corn–alfalfa–alfalfa; S-S-S, soybean–soybean–soybean; S-S-W, soybean–soybean–wheat; C-S, corn–soybean; CRP, conservation reserve program; PG, perennial grass.

ses and the chemical and nutrient analyses were completed at the USDA-ARS National Laboratory for Agriculture and the Environment. All analyses were run in duplicate with appropriate controls and standards.

After arrival in the laboratory, the composite samples were weighed and the gravimetric water content was determined (Topp and Ferré, 2002). An estimate of soil ρ_b was calculated based on sample volume and water content (Grossman and Reinsch, 2002). Soil was passed through an 8-mm sieve, removing plant material and rocks larger than the mesh openings. The removed material's weight was recorded. Representative 150-g subsamples were removed, placed in a plastic bag, and stored at 4°C for soil microbial biomass C (MBC) determination. Another representative portion was hand-sieved to pass a 2-mm sieve, air dried, and stored at 4°C until used for determining potentially mineralizable C (C_{min}) and N (N_{min}). The remainder of each soil sample was air dried, ground to pass a 2-mm sieve, bagged, and stored at 4°C until use.

Soil Analyses

The hydrometer method was used to determine soil texture (Gee and Or, 2002). Macroaggregate stability (MAS) (>0.25 mm) was measured using a modified Yoder sieving machine (Yoder, 1936), set to 30 strokes min^{-1} for 5 min (Nimmo and Perkins, 2002). A 25-g sample of air-dried 8-mm sieved soil was placed on top of a nest of four sieves with 2.0-, 1.0-, 0.5-, and 0.25-mm openings (sieve numbers 10, 18, 35, and 60, respectively). Physical disruption of aggregates was performed in deionized water to limit chemical dispersion of aggregates. Measurements were corrected for sand content.

The pH (Watson and Brown, 1998) and electrical conductivity (EC) (Whitney, 1998b) were determined using 20 g of air-dried soil ground to pass a 2-mm sieve and a 1:1 soil/water ratio with EC (SevenEasy Conductivity 8603, Mettler Toledo, Columbus, OH) and pH (Mettler Toledo) meters. Another 20-g soil subsample was extracted with Mehlich 3 (Mehlich, 1984) solution and P, K, Ca, and Mg concentrations were determined using inductively coupled plasma–optical emission spectroscopy (Optima 5300 DV, PerkinElmer, Thornhill, ON, Canada). Concentrations of Cu, Fe, Mn, and Zn were measured using inductively coupled plasma–optical emission spectroscopy after extracting 20 g of soil with diethylenetriaminepentaacetic acid (Whitney, 1998a). Soil inorganic N [$(NO_2 + NO_3)$ + NH^4] was extracted by following Keeny and Nelson (1987) and concentrations were determined via flow injection analysis (QuikChem 8500, Lachat Instruments, Loveland, CO). Total soil C and total N were measured by dry combustion (Tru-Mac CN Analyzer, Leco, St. Joseph, MI) using air-dried, ground soil and a methodology appropriate for the instrument. For any soil with a pH of >6.9, soil inorganic C was quantified (Sherrod et al., 2002); SOC was calculated as the difference between total and inorganic C. For pH $\leq$ 6.9, SOC was considered to be equal to total C content.

Microbial biomass C was measured on 8-mm sieved field-moist samples following soil fumigation and chemical extractions methods (Brookes et al., 1985) and a correction factor (K_c = 0.33) was applied to extracts to convert values to MBC (Vance et al., 1987) . A modified version of the method found in Zibilske (1994) was used to determine C_{min}. Potentially mineralizable C was measured on air-dried 2-mm hand-sieved soils following an aerobic 28-d incubation method using KOH base traps to absorb CO_2. Aliquots of the base traps were acidified and CO_2 concentration was measured using a gas chromatograph (Model 3800, Varian, Walnut Creek, CA) equipped with a CombiPal autosampler (CTC Analytics, Zwingen, Switzerland). Potentially mineralizable N was also measured during the same incubation according to Drinkwater et al. (1996). Mineral N [$(NO_2 + NO_3) + NH_4$] was determined colorimetrically using a flow injection system (Lachat Instruments). Air-dried, 2-mm sieved soil was used for assaying β-glucosidase (BG) activity according to Eivazi and Tabatabai (1988), as detailed by Deng and Popova (2011), and expressed as mg of *p*-nitrophenol released per kg soil per h of incubation.

Soil Management Assessment Framework

A detailed account of the SMAF can be found in Andrews et al. (2004). Ten SMAF indicators and their respective scoring curves or interpretative algorithms were used to calculate an overall SQI for this study. They were: MAS, ρ_b, pH, EC, extractable P and K, SOC, MBC, N_{min}, and BG activity. These indicators contribute to soil functionality with regards to crop productivity, water partitioning, and environmental buffering. Data were scored with previously published algorithms (Andrews et al., 2004; Stott et al., 2010; Wienhold et al., 2009) and used to compute indices for each sampling site. Soil taxonomic classification, soil texture, and general climate were used to select appropriate factors for indicator-scoring algorithms.

Selected organic matter factor classes, based on soil classification and used for scoring MAS, BG, MBC, N_{min}, and SOC, fell into three categories: (i) Houghton muck, (ii) Pewamo clay loam and Wallkill silt loam and (iii) all other soil series (Table 2). Texture, based on measurements for each site, were used to score MAS, ρ_b, BG, EC, MBC, N_{min}, and SOC. This approach resulted in four textural classes: (i) loams and sandy loams (>8% clay); (ii) silts and silt loams; (iii) clay loams, silty clay loams, silty clays, and clays (<40% clay); and (iv) clays (>40% clay). The climate factor, impacting the scoring for the biological indicators MBC, N_{min}, SOC, and BG, was uniform for all samples. The slope factor, used for scoring extractable P, was divided into four classes: 0 to 2, 2 to 5, 5 to 9, and 9 to 15% slope. The seasonal factor, impacting MBC, was also identical for all samples, which were collected in fall. Iron oxide, mineralogy, and weathering factors were uniform. The methods used to measure extractable P and EC were considered in scoring these indicators and did not vary in this study. Soil P, EC, and pH scoring were also partially dependent on crop selection.

Individual indicator scores, as well as an overall SQI, were calculated by summing scores and dividing by the number of measurements (10). Component SQI values were also calculated for soil physical (MAS and ρ_b), chemical reaction (pH and EC), biological and biochemical (SOC, MBC, N_{min}, and BG), and nutrient (extractable P and K) parameters (Stott et al., 2013).

Statistical Analysis

Soil quality indicator values and SQI scores were analyzed to determine crop rotation, tillage, and landscape position effects. Many of the variables were non-normally distributed and had heterogeneous error variance (heteroscedasticity) according to the Kolmogorov–Smirnov and Brown–Forsythe tests, respectively. To correct for non-normality and outliers, these variables were transformed using Box–Cox transformation (Box and Cox, 1964) using the %boxcoxar macro in SAS version 9.2 (SAS Institute, Cary, NC). Except in cases where the variables were heteroscedastic, ANOVA was carried out using PROC GLM in SAS version 9.2. Treatment means for heteroscedastic variables were determined using the Kruskal–Wallis nonparametric test PROC NPAR1WAY in SAS version 9.2. Heteroscedastic *x*-data were replaced by ranks according to the *x*-data's raw value with positive integers and then mean separation was determined for all data where significant effects were present ($P \leq 0.05$ for ANOVA and $\chi \leq 0.05$ for the Kruskal–Wallis test) using the "lsmeans" statement and the "lines" option in PROC GLM. For comparison with other studies, soil data were analyzed by depth (0–5 cm and 5–15 cm). For each analysis, data were sorted by depth in addition to each management practice.

RESULTS AND DISCUSSION

General Soil Quality Effects

Most soil indicator data for both the 0- to 5-cm and 5- to 15-cm depths had broad value ranges, with means being greater than the medians in almost all cases (Table 3), thus reflecting the non-normal distribution of data. Inclusion of four Histosol (muck) soil samples skewed the means upward for many indicators by having values that were high, outlying points. Total SQI scores were 17 points higher for Histosols than for other orders within the same farm, but some of the differences may have been related to the coincidence of Histosols within the toe-slope landscape position. Although most measured soil textures were consistent with typic pedons for each soil series (Table 2), there were occasional variations caused by natural variance within soil series, erosion, and deposition, accompanied by tillage mixing of the B- and Ap- horizons. Macroaggregate stability and ρ_b were physical parameters of interest because of their impact on soil structure and infiltration (Table 3). Despite wide ranges, most soils were well aggregated and ρ_b values were typical for these soils.

For fertility management assessment, pH, EC, N, P, and K were of primary interest, with additional measurements for Ca, Mg, Cu, Fe, Mn, and Zn contents. The pH measurements were normal for these soils (Table 2) according to the Web Soil Survey (Soil Survey Staff, 2013b). In the 5- to 15-cm depth,

Table 2. Soil series represented in this study by slope position, including taxonomic classification, texture, and drainage class from the published soil surveys (Soil Survey Staff, 2013a) and soil organic C (SOC), bulk density (ρ_b), and pH data from summary reports generated from the USDA-NRCS web soil survey (Soil Survey Staff, 2013b) for DeKalb County, IN.

Soil series	Taxonomic classification	Texture	Drainage	SOC			ρ_b†		pH‡	
				Mean	Range	Factor class	Mean	Range	Mean	Range
				—g kg^{-1}—			—g cm^{-3}—			
Sideslope										
Blount	Fine, illitic, mesic Aeric Epiaqualfs	Silt loam	Somewhat poor	13	5–16	3	1.45	1.30–1.60	6.5	5.6–7.3
Glynwood	Fine, illitic, mesic Aquic Hapludalfs	Silt loam	Moderately good	11	5–16	3	1.45	1.30–1.60	6.5	5.6–7.3
Morley	Fine, illitic, mesic Oxyaquic Hapludalfs	Silty clay loam	Moderately good	16	5–16	3	1.45	1.30–1.60	6.5	5.6–7.3
Till, outwash or flood plain										
Oshtemo	Coarse-loamy, mixed, active, mesic Typic Hapludalfs	Sandy loam	Good	8	5–16	3	1.40	1.20–1.60	6.5	5.6–7.3
Pewamo	Fine, mixed, active, mesic Typic Argiaquolls	Clay loam	Very poor	24	16–32	2	1.45	1.30–1.60	6.5	5.6–7.3
Rawson	Fine-loamy, mixed, active, mesic Oxyaquic Hapludalfs	Loam	Moderately good	13	5–16	3	1.50	1.40–1.60	5.8	5.6–7.3
Wallkill	Fine-loamy, mixed, superactive, nonacid, mesic Fluvaquentic Humaquepts	Silt loam	Very poor	37	5–53	2	1.45	1.30–1.60	6.5	5.6–7.3
Bottom of closed depressions										
Houghton	Euic, mesic Typic Haplosaprists	Muck	Very poor	395	210–475	1	0.45	0.15–0.60	6.9	6.6–7.3

† Bulk density was calculated via the whole-soil, moist, clod method.

‡ 1:1 suspension.

mean values for extractable P and K were classified as very high, although there were samples that fell within lower-level classifications (Sawyer et al., 2002; Vitosh et al., 1995). Extractable Ca and Mg concentrations were in excess of amounts considered adequate for plant growth by at least 10-fold for all samples (Vitosh et al., 1995). Micronutrients were at high levels for most soils, although there were a few soils that had low to marginal levels of Mn and Zn (Buchholz, 2004; Sawyer et al., 2002).

Five biological indicators were measured, as they are involved in organic matter and nutrient cycling. Soil organic C

Table 3. Measured soil indicators from the Cedar Creek watershed in northeastern Indiana, where 20 fields were sampled with six sample locations per field that transected potholes to include samples from three topographic positions for a total of 120 samples.

Depth	0–5 cm				5–15 cm			
	Mean	Median	Range	SD	Mean	Median	Range	SD
Physical soil indicators								
Clay, g kg^{-1}	270	260	145–444	72	290	275	132–489	79
Sand, g kg^{-1}	270	268	50–616	105	253	254	30–629	72
Bulk density, g cm^{-3}	1.1	1.1	0.5–1.5	0.2	1.4	1.4	0.5–1.7	0.2
Macroaggregate stability, %	46.6	44.7	12.9–88.1	18.0	50.2	49.9	16.4–95.8	19.0
Chemical soil indicators								
pH	6.5	6.6	4.8–7.9	0.7	6.4	6.4	4.9–8.1	0.7
Electrical conductivity, dS m^{-1}	0.28	0.27	0.12–0.52	0.09	0.21	0.20	0.10–0.44	0.07
Biological soil indicators								
Soil organic C, g kg^{-1}	27.9	21.2	12.1–228.6	28.6	24.1	16.8	9.2–249	31.4
Microbial biomass C, mg kg^{-1}	591	500	152–2166	364	323	281	28–1283	203
Mineralizable C, mg kg^{-1}	482	446	205–1308	181	310	290	23–591	95
Mineralizable N, mg kg^{-1}	39.2	38.4	–58.4 to 137.1†	23.1	39.2	38.7	–9.2 to 87.4	16.6
β-Glucosidase, mg *p*-nitrophenol kg^{-1} h^{-1}	172.8	159.3	4.0–439.6	60.8	81.7	71.6	6.3–203	33.3
Nutrient soil indicators								
Total N, g kg^{-1}	2.6	2.0	1.0–15.0	1.9	2.3	2.0	1.0–17.0	2.1
Extractable P, mg kg^{-1}	104	96	16–351	57	56	52	8.5–231	36.2
Extractable K, mg kg^{-1}	612	536	154–1569	285	305	258	101–912	167
Extractable Ca, mg kg^{-1}	4351	4072	979–9958	1833	4390	4127	1,009–11,040	2080
Extractable Mg, mg kg^{-1}	684	649	107–1413	253	662	622	92–1,351	270
Extractable Fe, mg kg^{-1}	83.3	66.4	18.8–397.2	64.3	88.8	65.6	21.3–399	71.1
Extractable Mn, mg kg^{-1}	29.8	26.9	4.9–94.8	17.9	23.1	21.1	0.5–65.5	14.0
Nutrient soil indicators								
Extractable Cu, mg kg^{-1}	6.9	5.9	1.6–22.2	4.2	5.6	3.8	0.2–30.4	6.0
Extractable Zn, mg kg^{-1}	2.7	2.3	0.7–9.0	1.4	2.0	1.5	0.4–7.3	1.5
SMAF scores‡								
Bulk density	0.95	0.99	0.53–0.99	0.10	0.63	0.61	0.26–0.99	0.24
Macroaggregation	0.85	0.90	0.34–1.00	0.17	0.92	1.00	0.42–1.00	0.13
pH	0.87	0.92	0.09–1.00	0.16	0.87	0.93	0.07–1.00	0.15
Electrical conductivity	1.00	1.00	1.00	0.00	1.00	1.00	1.00	0.00
Soil organic C	0.61	0.61	0.15–1.00	0.25	0.45	0.39	0.09–1.00	0.27
Microbial biomass C	0.94	0.99	0.15–1.00	0.14	0.70	0.75	0.05–1.00	0.28
Mineralizable N	0.95	1.00	0.01–1.00	0.21	0.97	1.00	0.01–1.00	0.16
β-Glucosidase	0.26	0.22	0.02–0.89	0.19	0.08	0.06	0.02–0.81	0.08
Extractable P	0.96	1.00	0.01–1.00	0.14	0.94	1.00	0.39–1.00	0.14
Extractable K	1.00	1.00	0.93–1.00	0.01	0.95	1.00	0.66-1.00	0.08
Soil quality indices								
Total	0.84	0.84	0.65–0.99	0.07	0.75	0.75	0.61–0.95	0.08
Physical sector	0.90	0.93	0.62–1.00	0.10	0.78	0.78	0.46–1.00	0.15
Chemical sector	0.93	0.96	0.55–1.00	0.08	0.94	0.97	0.54–1.00	0.08
Biological sector	0.69	0.69	0.40–0.97	0.12	0.55	0.57	0.20–0.83	0.13
Nutrient sector	0.98	1.00	0.51–1.00	0.07	0.94	1.00	0.58–1.00	0.09

† Negative numbers for potentially mineralizable N represent N immobilization.

‡ Soil Management Assessment Framework (SMAF) is an algorithm based on measured soil properties that gives a soil quality score, where 0 is the lowest quality and 1 is the highest quality. Sector soil quality indices are averages of SMAF scores that correspond to the appropriate sector. Bulk density and macroaggregation SMAF scores correspond to the physical soil quality sector; pH and electrical conductivity SMAF scores correspond to the chemical soil quality sector; soil organic C, microbial biomass C, mineralizable N, and β-glucosidase SMAF scores correspond to the biological soil quality sector; and extractable P and extractable K SMAF scores correspond to the nutrient soil quality sector. The total soil quality index is an average of all soil quality sector scores.

concentrations were within the ranges observed in these soils, although they have decreased by more than 50% compared with historic levels in Midwestern Mollisols (David et al., 2009). Cedar Creek BG activity was considerably less than that found in other Midwestern corn–soybean agroecosystems with similar climate, soil type, and management (Dodor and Tabatabai, 2005; Eivazi and Tabatabai, 1990; Stott et al., 2010). When these results were compared with a soil quality assessment in the South Fork of the Iowa River (Stott et al., 2011), which has a similar landscape characterized by closed depressions and similar sampling depths, C_{min} was greater in Cedar Creek soils and SOC, MBC, N_{min}, and BG activity were lower. Both sites were sampled in fall after harvest; however, Cedar Creek was sampled later in the season and therefore, lower soil temperatures may explain some of the observed differences in the biological indicators.

There were a considerable number of highly significant correlations at both the 0- to 5-cm and 5- to 15-cm depths (Table 4). Macroaggregate stability and ρ_b were significantly correlated with several nutrients and all biological indicators except N_{min}. Although EC was correlated with biological and nutrient parameters, pH was not, except for Ca and Fe. Soil organic C content was significantly correlated with nutrients such as K, Ca, Mg, Fe, and Zn and with MBC and BG activity but not with other biological indicators.

A SMAF score of 1.0 indicates that an individual indicator or group of indicators is performing at 100% or its maximum inherent potential. Similarly, a score of 0.80 indicates that the soil is functioning at 80% of the optimum. For physical indicators, the SMAF–MAS and SMAF–ρ_b scoring curves are represented by more-is-better and less-is-better sigmoidal shapes, respectively. Macroaggregation levels for most soils represented in this study would have to drop below 70% to score less than 1.0. The SMAF–MAS scores for these soils averaged 0.88 at the 5- to 15-cm depth and exhibited a wide range, with some soils performing poorly (<50% of the optimum). Bulk densities above 1.3 g cm^{-3} would be required in most mineral soils in this study to score below 0.99. However, there were no SMAF–ρ_b indicators that scored the optimum, even though some were near-optimum (>0.90). Mean ρ_b scores dropped from 0.95 in the shallower depth to 0.78 in the Ap (5–15 cm) horizon. Overall ρ_b scores were 0.17 lower than what was reported for the Ap horizon within the South Fork watershed (Stott et al., 2011). We suggest this may have reflected a slightly greater fraction of Alfisols within the Cedar Creek watershed than within the South Fork watershed, where more sites were classified as Mollisols.

For chemical indicators, EC, and pH, the SMAF scoring curves had a parabolic shape and an optimum middle range, with extreme values resulting in suboptimal scores (Karlen and Stott, 1994). Only pH displayed SMAF scores that varied, as all EC measurements were 1.0, which represented measurements below 0.72 dS m^{-1} (Andrews et al., 2002). The SMAF–pH indicator scores averaged 0.87 at both depths, which was similar to those in the South Fork watershed (Stott et al., 2011).

All biological properties had SMAF indicator scoring curves with a sigmoidal more-is-better shape (Andrews et al., 2002; Karlen and Stott, 1994; Stott et al., 2010). For the majority of

Table 4. Correlation matrix for the measured soil quality indicators at the 0- to 5-cm (above the diagonal line) and 5- to 15-cm depths (below the line) from the Cedar Creek watershed in northeastern Indiana.

	Clay†	Sand	Silt	ρ_b	MAS	pH	EC	SOC	MBC	C_{min}	N_{min}	BG	TN	Extracted P	K	Ca	Mg	Fe	Mn	Cu	Zn
Clay	–	0.30	0.03	0.06	0.01	0.01	0.01	0.02	0.00	0.03	0.01	0.00	0.02	0.04	0.13	0.13	0.19	0.25	0.00	0.06	0.02
Sand	0.53	–	0.54	0.00	0.00	0.02	0.00	0.04	0.00	0.00	0.02	0.02	0.03	0.00	0.07	0.01	0.08	0.07	0.02	0.08	0.02
Silt	0.00	0.43	–	0.04	0.00	0.01	0.01	0.11	0.00	0.01	0.05	0.02	0.10	0.01	0.00	0.03	0.00	0.01	0.04	0.02	0.00
ρ_b	0.16	0.15	0.01	–	0.00	0.04	0.16	0.39	0.18	0.05	0.00	0.10	0.41	0.06	0.19	0.19	0.24	0.27	0.02	0.00	0.13
MAS	0.00	0.02	0.03	0.16	–	0.00	0.00	0.09	0.25	0.13	0.10	0.21	0.11	0.02	0.00	0.06	0.03	0.02	0.01	0.01	0.04
pH	0.01	0.02	0.01	0.02	0.01	–	0.01	0.03	0.00	0.05	0.02	0.03	0.03	0.02	0.08	0.07	0.01	0.30	0.02	0.02	0.02
EC	0.15	0.11	0.00	0.15	0.01	0.06	–	0.12	0.12	0.04	0.00	0.07	0.16	0.02	0.08	0.20	0.10	0.05	0.03	0.00	0.07
SOC	0.04	0.06	0.02	0.59	0.09	0.02	0.05	–	0.19	0.01	0.05	0.06	0.96	0.00	0.11	0.34	0.27	0.45	0.03	0.00	0.19
MBC	0.03	0.07	0.04	0.48	0.38	0.00	0.08	0.46	–	0.53	0.22	0.42	0.25	0.04	0.00	0.16	0.19	0.08	0.02	0.00	0.09
C_{min}	0.00	0.00	0.01	0.22	0.24	0.01	0.09	0.20	0.42	–	0.25	0.25	0.02	0.05	0.01	0.06	0.04	0.00	0.01	0.00	0.01
N_{min}	0.01	0.05	0.05	0.14	0.16	0.02	0.15	0.02	0.16	0.29	–	0.22	0.02	0.03	0.00	0.02	0.02	0.02	0.07	0.00	0.01
BG	0.04	0.09	0.04	0.23	0.09	0.09	0.12	0.15	0.31	0.11	0.20	–	0.10	0.00	0.02	0.15	0.17	0.02	0.00	0.00	0.06
TN	0.06	0.08	0.02	0.63	0.11	0.01	0.07	0.96	0.48	0.22	0.04	0.17	–	0.01	0.14	0.38	0.27	0.42	0.01	0.00	0.22
Ext. P	0.03	0.00	0.01	0.07	0.00	0.02	0.06	0.00	0.01	0.00	0.08	0.02	0.01	–	0.33	0.01	0.00	0.05	0.11	0.00	0.08
Ext. K	0.21	0.11	0.00	0.27	0.02	0.01	0.19	0.09	0.05	0.07	0.12	0.03	0.14	0.24	–	0.15	0.10	0.24	0.00	0.01	0.17
Ext. Ca	0.23	0.15	0.00	0.41	0.09	0.12	0.28	0.37	0.28	0.23	0.13	0.23	0.45	0.03	0.21	–	0.47	0.14	0.03	0.00	0.14
Ext. Mg	0.35	0.32	0.03	0.40	0.13	0.04	0.22	0.27	0.29	0.10	0.18	0.32	0.31	0.02	0.23	0.47	–	0.19	0.03	0.08	0.16
Ext. Fe	0.27	0.20	0.01	0.57	0.10	0.20	0.09	0.48	0.24	0.09	0.03	0.05	0.50	0.12	0.30	0.25	0.27	–	0.01	0.04	0.18
Ext. Mn	0.01	0.00	0.01	0.02	0.00	0.01	0.00	0.07	0.01	0.00	0.03	0.03	0.06	0.05	0.00	0.08	0.05	0.08	–	0.01	0.00
Ext. Cu	0.09	0.13	0.04	0.05	0.04	0.00	0.06	0.00	0.07	0.01	0.01	0.05	0.00	0.00	0.01	0.05	0.19	0.07	0.05	–	0.27
Ext. Zn	0.07	0.13	0.05	0.20	0.08	0.00	0.15	0.10	0.21	0.09	0.14	0.18	0.11	0.07	0.10	0.17	0.23	0.19	0.03	0.54	–

† Correlation coefficients (R^2) for soil quality indicators. Correlations with $R^2 \geq 0.25$ are underlined.

‡ ρ_b, bulk density; MAS, macroaggregate stability; EC, electrical conductivity; SOC, soil organic C; MBC, microbial biomass carbon; C_{min}, potentially mineralizable C; N_{min}, potentially mineralizable N; BG, β-glucosidase activity; TN, total N; Ext., extracted.

mineral soils in this study, a SOC content of about 50 g C kg^{-1} would equate to a score of 1.0. Overall, the mean SOC scores were 0.61 and 0.45 for 0- to 5- and 5- to 15-cm depths, respectively (Table 3). The mean score for 5 to 15 cm was 0.18 lower than the South Fork watershed (Stott et al., 2011), which had similar soils and cropping systems, although they are in line with the mean scores found in an earlier Iowa study (Karlen et al., 2008). Histosols in our study individually scored 0.98 as a result of their high SOC content (mean: 235 g C kg^{-1}). Most individual scores at the 0- to 5-cm depth were >0.90 for the SMAF–MBC and SMAF–N_{min} scores. The trend continued at the 5- to 15-cm depth for N_{min}, although the mean MBC score was 0.24 lower than in the shallower depth. Indicator scores for SMAF–BG were quite low, with means of 0.26 and 0.08 in 0- to 5- and 5- to 15-cm depths.

Nutrient scoring curves were parabolic and had optimal middle ranges and suboptimal extremes. The SMAF–P score had the widest range possible at the 0- to 5-cm depth (0.01–1.00), and the 5- to 15-cm depth also had a wide range (0.39–1.00). Low scores were almost invariably caused by high soil P concentrations that, on slopes, would provide a high risk of P loss via runoff to nearby ditches and streams. Potassium scores were high, with a mean of 1.00 and 0.95 at shallower and deeper depths, respectively. Both SMAF–P and SMAF–K mean scores were comparable to those found in the South Fork watershed (Stott et al., 2011).

Overall, most soils were performing adequately, with total SQI scores at 84 and 75% of the optimum at 0 to 5 and 5 to 15 cm, respectively, but with broad ranges. These scores were comparable to those found in other studies with similar crop and soil management systems (Cambardella et al., 2004; Jokela et al., 2011; Karlen et al., 2008; Stott et al., 2011). Total SQI is weighted toward biological indicators, with four measurements, whereas the physical, chemical, and nutrient sectors each include two representative indicators; thus it is informative to split SQI into sectors. The physical sector SQI, which includes MAS and ρ_b, had higher mean scores than total SQI at the 0- to 5-cm depth, but was lower at the 5- to 15-cm depth. The chemical sector SQI, which included pH and EC, was controlled predominately by pH, as EC was at the optimum (1.0) for all soils, with a similar range for both depths. The SMAF–pH indicator score ranged from 0.07 to 1.00, with a mean of 0.87 at 0 to 5 and 5 to 15 cm; indicating that some sites were performing poorly with respect to the impact of chemical reactivity on soil functions such as productivity and nutrient cycling. The biological sector SQI values, which include SOC, MBC, N_{min}, and BG activity, had the lowest scores of all components, with mean values of 0.69 and 0.55 at 0 to 5 and 5 to 15 cm, respectively.

Crop Rotation Effects

When the data were sorted by crop rotation (Table 5), the corn and 2-yr alfalfa (*Medicago sativa* L.) (C-A-A) rotation had significantly greater ρ_b at 0 to 5 cm than 3 yr of soybean (S-S-S), soybean–soybean–winter wheat (*Triticum aestivum* L.) (S-S-W), corn–soybean–winter wheat (C-S-W), corn–soybean (C-S), or perennial grass rotations (PG). Macroaggregate stability values followed a different pattern. Perennial grass plots had significantly greater values than any other rotation at both sampling depths. The C-S-W rotations had the lowest values within the 0- to 5-cm depth, and although both C-S and C-S-W rotation had low values within the 5- to 15-cm depth increment, the values were not significantly lower than those in other treatments (Table 5). Differences in chemical soil indicators were small and varied by indicator and sampling depth. For biological indicators, PG generally had greater mean values than the other rotations, even though the differences were not always significant. Corn–soybean rotations generally had lower mean values for MBC, C_{min}, and N_{min}, but C-A-A had the lowest BG mean for both depth increments. Crop rotation had no effect on SOC or total N at either depth. Extractable P and K were greatest in C-S-W, S-S-S, and S-S-W rotations at both depths. One of the C-S-W sites received regular manure applications, which probably gave rise to the high extractable P (Table 1). Differences in Ca, Mg, and micronutrients were small when present and would not limit crop growth or SMAF scores for any rotation.

Aside from P and K scores, for the indicators and depths that did differ significantly, PG sites generally had significantly higher scores than C-S systems, with other crop rotations being no different from PG in several instances. As expected, all scores were lower for the 5- to 15-cm depth than for the 0- to 5-cm depth, except for MAS. Macroaggregate stability scores for both depths were highest for PG and significantly lower for C-S-W but other systems were intermediate between these two extremes. For SOC, PG sites had the highest scores, whereas C-S, C-A-A, and C-S-W sites had the lowest scores at 0 to 5 cm. Other rotations fell in between these values. Again, as expected, scores were overall lower for 5 to 15 cm but there were no significant differences among systems. At the shallower depth, PG, S-S-S, and S-S-W had significantly higher BG scores, with C-S, C-A-A, and C-S-W rotations having the lowest. For 5 to 15 cm, PG and S-S-W had the highest BG scores, with C-S, C-A-A, and C-S-W being significantly lower and S-S-S in between. In addition, BG scores for 5 to 15 cm were 50% or less than the 0 to 5 cm BG scores.

Overall, mean total SQI for the shallow depth was highest in PG, lowest in rotations with corn, and intermediate in the remaining rotations. The pattern was nearly the same for 5 to 15 cm, but less pronounced. Physical sector SQIs were highest in PG, lowest in C-S and C-S-W, and intermediate for other rotations within both depth increments. Biological SQIs followed a similar trend for both depths, with PG having the highest SQIs and C-S sites the lowest. Chemical and nutrient sector SQIs did not differ according to rotation.

Tillage Effects

Tillage practices for row crops within the watershed fell into two broad categories: fall chisel–spring disk tillage (C-D) and no-till (NT). There were also several untilled sites where pe-

Table 5. Means of soil indicators, Soil Management Assessment Framework (SMAF) indicator scores, and soil quality indices (SQI) by depth and crop rotation within the Cedar Creek watershed.

	0–5 cm						5–15 cm					
Rotation	**C-S†**	**C-A-A**	**C-S-W**	**PG**	**S-S-S**	**S-S-W**	**CS**	**C-A-A**	**C-S-W**	**PG**	**S-S-S**	**S-S-W**
n	30	6	60	12	6	6	30	6	60	12	6	6
Physical soil indicators												
Clay, g kg-1	268ab‡	243abc	293a	216c	245abc	215bc	296ab	255abc	307a	242c	274abc	236bc
Sand, g kg^{-1}	277	236	269	293	263	234	234	229	255	286	289	256
Silt, g kg^{-1}	456ab	521a	438b	492ab	493ab	551a	470a	516a	438b	472ab	437ab	508a
Bulk density, g cm^{-3}	1.13b	1.27a	1.07b	1.04bc	0.91c	1.00bc	1.35	1.37	1.38	1.33	1.33	1.37
Macroaggregate stability, %	49.6b	46.8bc	39.1c	71.0a	48.8bc	36.0bc	43.1c	54.8bc	43.3c	85.1a	61.2b	52.0bc
Chemical soil indicators												
pH	6.5	6.1	6.6	6.5	6.1	6.4	6.5ab	6.1ab	6.5a	6.6ab	5.9b	6.2ab
Electrical conductivity, dS m^{-1})	0.26	0.28	0.29	0.27	0.28	0.25	0.16bc	0.15abc	0.19a	0.14c	0.19abc	0.14c
Biological soil indicators												
Soil organic C, g kg^{-1}	37.3	17.6	23.7	35.4	24.9	20.6	35.2	15.2	21.0	21.6	20.2	17.2
Microbial biomass C, mg kg^{-1}	453.1c	524.0b	529.7b	1424.2a	401.8bc	491.2bc	233.5b	341.5ab	257.2b	558.4a	270.4b	181.3b
Mineralizable C, mg kg^{-1}	381.0b	416.8b	457.2b	841.5a	478.2b	439.6b	261.7b	287.9b	304.5b	416.5a	309.2b	287.3b
Mineralizable N, mg kg^{-1}	28.2c	44.4bc	32.4bc	69.7a	49.7ab	47.4ab	33.0b	37.8ab	36.2ab	46.9a	44.7ab	39.1ab
β-Glucosidase, mg *p*-nitrophenol kg^{-1} h^{-1}	1765cd	129d	155cd	267a	230ab	193bc	89.0ab	56.7c	78.7bc	99.8a	78.6abc	67.4bc
Nutrient soil indicators												
Total N, g kg^{-1}	3.10	2.00	2.33	3.33	2.50	2.17	2.80	1.67	2.12	2.00	2.33	1.83
Extractable P, mg kg^{-1}	83.0b	40.1c	114.6a	55.5c	150.9a	109.6ab	44.7b	29.3b	59.1a	25.6b	83.1a	50.4ab
Extractable K, mg kg^{-1}	477c	493bc	592b	407c	976a	723ab	224cd	262bcd	301b	170d	469a	284abc
Extractable Ca, mg kg^{-1}	3827	2932	4174	4266	4160	3702	3665	2981	4301	3796	3702	3581
Extractable Mg, mg kg^{-1}	717	469	676	794	621	651	683	454	684	691	547	602
Extractable Fe, mg kg^{-1}	59.3	67.8	65.5	80.8	87.1	50.2	65.6ab	62.4ab	71.3ab	61.9ab	119.5a	51.9b
Extractable Mn, mg kg^{-1}	22.6b	53.7a	23.2b	27.3b	24.5b	28.0ab	15.8b	40.4a	17.1b	19.9ab	25.4ab	29.5ab
Nutrient soil indicators												
Extractable Cu, mg kg^{-1}	5.55	8.03	5.77	5.71	6.58	5.66	3.54b	2.54b	3.83ab	6.58a	3.00ab	2.08b
Extractable Zn, mg kg^{-1}	2.27b	2.26b	2.28b	2.69ab	4.12a	1.95b	1.63ab	1.07bc	1.56abc	2.08a	2.50a	0.90c
SMAF scores§												
Bulk density	0.91	0.91	0.97	1.00	1.00	1.00	0.64b	0.74ab	0.68ab	0.81a	0.78ab	0.71ab
Macroaggregation	0.93bc	0.97ab	0.90c	1.00a	0.98a	0.92bc	0.97ab	0.99ab	0.95b	1.00a	1.00a	0.97ab
pH	0.89bc	0.84c	0.83c	0.96a	0.94abc	0.96ab	0.91	0.86	0.89	0.92	0.91	0.94
Electrical conductivity	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Soil organic C	0.50b	0.46b	0.57b	0.91a	0.67ab	0.66ab	0.34	0.34	0.44	0.49	0.46	0.49
Microbial biomass C	0.92c	0.99ab	0.96ab	1.00a	0.90bc	1.00a	0.67d	0.92ab	0.79c	0.99a	0.81bcd	0.80bcd
Mineralizable N	0.98	1.00	0.98	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1.00
β-Glucosidase	0.18b	0.16b	0.16b	0.58a	0.40a	0.39a	0.07b	0.05b	0.06b	0.09a	0.07ab	0.10a
Extractable P	1.00a	0.98ab	0.98ab	0.99a	0.95b	0.99ab	0.96abc	0.91c	0.99a	0.95bc	0.99a	0.97abc
Extractable K	1.00	1.00	1.00	1.00	1.00	1.00	0.94ab	0.91bc	0.97ab	0.86c	1.00a	0.99ab
SQIs¶												
Total	0.81d	0.81cd	0.80d	0.95a	0.86bc	0.89b	0.71b	0.72ab	0.72b	0.78a	0.78ab	0.76ab
Physical sector	0.88c	0.91bc	0.89c	1.00a	0.99ab	0.94abc	0.77b	0.85ab	0.77b	0.89a	0.88ab	0.78ab
Chemical sector	0.95bc	0.92c	0.91c	0.98a	0.97abc	0.98ab	0.96	0.93	0.95	0.96	0.96	0.97
Biological sector	0.64d	0.66cd	0.67cd	0.88a	0.74bc	0.78b	0.51b	0.57ab	0.55b	0.66a	0.56ab	0.61ab
Nutrient sector	1.00a	0.99ab	0.99ab	1.00a	0.97b	0.99ab	0.92ab	0.88c	0.97abc	0.87d	1.00a	0.97ab

† Cover crops have been added to some C-S-W sites relatively recent (<5 yr); C, corn; S, Soybean; W, Winter Wheat; A, Alfalfa; PG, perennial grass, multiple species.

‡ Different letters within a row and for a given depth indicate significantly different means as determined by ANOVA at $P = 0.05$ or the Kruskal–Wallis test at $\chi \leq 0.05$. Rows with no letters had no significant differences between means within a given depth.

§ Soil Management Assessment Framework is an algorithm based on measured soil properties that gives a soil quality score, where 0 is the lowest quality and 1 is the highest quality. Sector soil quality indices are averages of SMAF scores that correspond to the appropriate sector. Bulk density and macroaggregation SMAF scores correspond to the physical soil quality sector; pH and electrical conductivity SMAF scores correspond to the chemical soil quality sector; soil organic C, microbial biomass C, mineralizable N, and β-glucosidase SMAF scores correspond to the biological soil quality sector; and extractable P and extractable K SMAF scores correspond to the nutrient soil quality sector. The total soil quality index is an average of all soil quality sector scores.

¶ Soil quality indices are the summation divided by the number of the individual SMAF indicator scores, either total or by sector; a score of 1.0 is considered optimum.

Table 6. Means of soil indicators, Soil Management Assessment Framework (SMAF) scores and soil quality indices (SQI) by depth and soil management systems within the Cedar Creek watershed.

	0–5 cm			5–15 cm		
Soil management system†	**C-D**	**NT**	**PG**	**C-D**	**NT**	**PG**
n	36	72	12	36	72	12
Physical soil indicators						
Clay, g kg^{-1}	261b ‡	288a	216c	284ab	304a	242b
Sand, g kg^{-1}	251	280	293	248	251	286
Silt, g kg^{-1}	487a	432b	492ab	468	445	472
Bulk density, g cm^{-3}	1.08	1.09	1.04	1.40	1.35	1.34
Macroaggregate stability, %	44.6b	41.2b	71.0a	46.6b	44.2b	85.1a
Chemical soil indicators						
pH	6.33b	6.66a	6.53ab	6.28	6.55	6.58
Electrical conductivity, dS m^{-1}	0.27	0.26	0.25	0.16b	0.19a	0.14b
Biological soil indicators						
Soil organic C, g kg^{-1}	20.3b	21.9b	32.0a	16.4	18.3	17.6
Microbial biomass C, mg kg^{-1}	529.7b	474.2c	1424.2a	286.2b	298.4b	591.8a
Mineralizable C, mg kg^{-1}	481.4b	408.9c	852.8a	305.3b	279.3b	416.5a
Mineralizable N, mg kg^{-1}	41.5b	30.7c	71.9a	35.2	36.7	46.9
β-Glucosidase, mg *p*-nitrophenol kg^{-1} h^{-1}	168.0b	157.8b	266.6a	71.2b	86.5a	99.8a
Nutrient soil indicators						
Total N, g kg^{-1}	2.29	2.72	3.33	1.94	2.55	2.00
Extractable P, mg kg^{-1}	98.5a	104.7a	55.5b	45.6b	60.7a	25.6c
Extractable K, mg kg^{-1}	606a	549a	407b	295a	270a	170b
Extractable Ca, mg kg^{-1}	3796	4112	4266	3741	4140	3796
Extractable Mg, mg kg^{-1}	596	643	747	577	625	612
Extractable Fe, mg kg^{-1}	77.8	86.4	90.0	81.7	98.7	68.2
Extractable Mn, mg kg^{-1}	30.0a	20.7b	27.3ab	23.8a	15.1b	19.9ab
Extractable Cu, mg kg^{-1}	5.97	5.76	5.71	3.61b	3.40b	6.58a
Extractable Zn, mg kg^{-1}	2.23	2.41	2.79	1.45	1.62	2.08
SMAF scores§						
Bulk density	0.95	0.96	1.00	0.66b	0.70ab	0.81a
Macroaggregation	0.87b	0.80c	1.00a	0.97ab	0.96b	1.00a
pH	0.89b	0.90b	0.96a	0.89	0.90	0.92
Electrical conductivity	1.00	1.00	1.00	1.00	1.00	1.00
Soil organic C	0.54b	0.57b	0.91a	0.38	0.44	0.49
Microbial biomass C	0.96ab	0.94b	1.00a	0.79b	0.75b	0.99a
Mineralizable N	0.99	0.98	1.00	0.99	1.00	1.00
β-Glucosidase	0.26b	0.20c	0.62a	0.06b	0.07b	0.09a
Extractable P	0.98	0.99	0.99	0.97ab	0.99a	0.95b
Extractable K	1.00	1.00	1.00	1.00	1.00	1.00
SQIs¶						
Total	0.82b	0.80b	0.95a	0.71b	0.74ab	0.78a
Physical sector	0.91b	0.88c	1.00a	0.78b	0.79b	0.89a
Chemical sector	0.95b	0.95b	0.98a	0.95	0.95	0.96
Biological sector	0.68b	0.66b	0.88a	0.54b	0.55b	0.66a
Nutrient sector	0.99	0.99	1.00	0.97a	0.98a	0.94b

† C-D, fall chisel–spring disk tillage; NT, no-till; PG, perennial grass in either buffer zones or land in the Conservation Reserve Program.

‡ Different letters within a row and for a given depth indicate significantly different means as determined by ANOVA at $P = 0.05$ or the Kruskal–Wallis test at $\chi \leq 0.05$. Rows with no letters had no significant differences between means within a given depth.

§ Soil Management Assessment Framework is an algorithm based on measured soil properties that gives a soil quality score, where 0 is the lowest quality and 1 is the highest quality. Sector soil quality indices are averages of SMAF scores that correspond to the appropriate sector. Bulk density and macroaggregation SMAF scores correspond to the physical soil quality sector; pH and electrical conductivity SMAF scores correspond to the chemical soil quality sector; soil organic C, microbial biomass C, mineralizable N, and β-glucosidase SMAF scores correspond to the biological soil quality sector; and extractable P and extractable K SMAF scores correspond to the nutrient soil quality sector. The total soil quality index is an average of all soil quality sector scores.

¶ Soil quality indices are the summation divided by the number of the individual SMAF indicator scores, either total or by sector; a score of 1.0 is considered optimum.

Table 7. Means of soil indicators, Soil Management Assessment Framework (SMAF) indicator scores, and soil quality indices (SQI) by depth and landscape position within potholes in the Cedar Creek watershed (n = 40).

	0–5 cm			5–15 cm		
Landscape position	**Summit**	**Mid-slope**	**Toe-slope**	**Summit**	**Mid-slope**	**Toe-slope**
Physical soil indicators						
Clay, g kg^{-1}	235b†	261b	315a	240c	283b	346a
Sand, g kg^{-1}	319a	269b	221c	312a	263b	186c
Silt, g kg^{-1}	446	470	465	448	454	468
Bulk density, g cm^{-3}	1.15a	1.10a	0.99b	1.48a	1.41b	1.22c
Macroaggregate stability, %	43.0b	41.7b	51.4a	39.5b	51.6a	56.0a
Chemical soil indicators						
pH	6.51	6.62	6.42	6.31	6.60	6.41
Electrical conductivity, dS m^{-1}	0.23b	0.25b	0.30a	0.14c	0.17b	0.21a
Biological soil indicators						
Soil organic C, g kg^{-1}	17.8c	22.5b	43.3a	13.3c	18.8b	40.2a
Microbial biomass C, mg kg^{-1}	468b	546b	760a	189c	278b	379a
Mineralizable C, mg kg^{-1}	450	452	503	267b	298b	364a
Mineralizable N, mg kg^{-1}	36.8	37.3	43.3	30.7b	35.8b	45.3a
β-Glucosidase, mg *p*-nitrophenol kg^{-1} h^{-1}	155b	163b	201a	66.9c	80.2b	97.9a
Nutrient soil indicators						
Total N, g kg^{-1}	1.80c	2.20b	3.83a	1.35c	1.90b	3.50a
Extractable P, mg kg^{-1}	91.0b	83.2b	117.3a	44.6b	43.7b	64.3a
Extractable K, mg kg^{-1}	482b	451b	783a	205b	237b	392a
Extractable Ca, mg kg^{-1}	3041c	4054b	5180a	2759c	4064b	5459a
Extractable Mg, mg kg^{-1}	514c	711b	826a	463c	700b	824a
Extractable Fe, mg kg^{-1}	53.9b	70.2b	126.8a	58.4b	74.2b	133.9a
Extractable Mn, mg kg^{-1}	21.2b	24.2ab	29.7a	18.2	17.6	20.2
Extractable Cu, mg kg^{-1}	4.48b	6.65a	6.70a	2.50b	4.22a	4.88a
Extractable Zn, mg kg^{-1}	1.74c	2.41b	3.21a	1.18b	1.48b	2.30a
SMAF scores‡						
Bulk density	0.94	0.96	0.97	0.62b	0.67b	0.79a
Macroaggregation	0.79b	0.88a	0.88a	0.84b	0.96a	0.95a
pH	0.90	0.89	0.91	0.89	0.91	0.90
Electrical conductivity	1.00	1.00	1.00	1.00	1.00	1.00
Soil organic C	0.51b	0.57b	0.69a	0.31c	0.43b	0.62a
Microbial biomass C	0.94	0.95	0.97	0.78	0.79	0.82
Mineralizable N	0.99	0.99	0.98	0.99	0.99	1.00
β-Glucosidase	0.21	0.21	0.20	0.07	0.07	0.10
Extractable P	0.99	0.99	0.98	0.96b	0.97b	1.00a
Extractable K	1.00	1.00	1.00	1.00	1.00	1.00
SQIs§						
Total	0.80b	0.83ab	0.84a	0.67c	0.73b	0.79a
Physical sector	0.87b	0.92a	0.93a	0.72c	0.80b	0.86a
Chemical sector	0.95	0.95	0.96	0.95	0.96	0.95
Biological sector	0.67b	0.69ab	0.72a	0.50b	0.55b	0.62a
Nutrient sector	0.99	0.99	0.99	0.96b	0.97b	1.00a

† Different letters within a row and for a given depth indicate significantly different means as determined by ANOVA at P = 0.05 or the Kruskal–Wallis test at $\chi \leq 0.05$. Rows with no letters had no significant differences between means within a given depth.

‡ Soil Management Assessment Framework is an algorithm based on measured soil properties that gives a soil quality score, where 0 is the lowest quality and 1 is the highest quality. Sector soil quality indices are averages of SMAF scores that correspond to the appropriate sector. Bulk density and macroaggregation SMAF scores correspond to the physical soil quality sector; pH and electrical conductivity SMAF scores correspond to the chemical soil quality sector; soil organic C, microbial biomass C, mineralizable N, and β-glucosidase SMAF scores correspond to the biological soil quality sector; and extractable P and extractable K SMAF scores correspond to the nutrient soil quality sector. The total soil quality index is an average of all soil quality sector scores.

§ Soil quality indices are the summation divided by the number of the individual SMAF indicator scores, either total or by sector; a score of 1.0 is considered optimum.

rennial grasses were planted as part of the Conservation Reserve Program as buffer or filter strip areas. These sites were all classified as PG for crop rotation comparisons. Among physical soil indicators, only percent clay and MAS exhibited significant differences, with PG sites having significantly less clay and significantly higher MAS than any other rotation regardless of tillage at both depths (Table 6). Perennial grass sites had consistently higher MAS at 0 to 5-cm and 5 to 15-cm than C-D or NT sites. Differences in pH at 0 to 5 cm and EC at 5 to 15 cm were statistically significant and translated into modest differences in SMAF scores. Significant differences were detected for all soil biological indicators at 0 to 5 cm and some indicators at 5 to 15 cm. For SOC and N_{min} at 0 to 5 cm and MBC, C_{min}, and BG at both depths, PG sites were significantly greater than C-D and NT sites. For SOC and BG at 0 to 5 cm and MBC and C_{min} at 5 to 15 cm, C-D and NT were no different. For BG at 5 to 15 cm, NT was greater than C-D. For MBC, C_{min}, and N_{min} at 0 to 5 cm, C-D was greater than NT. Manganese was the only nutrient SQI that differed according to tillage practice. Extractable P and K in PG was significantly less than that in C-D or NT sites at both depths, but not below levels that would limit crop growth or SMAF scores. There was no significant difference between C-D and NT for extractable P at either depth, so the use of tillage as a means of reducing surface P concentration may not be applicable in all cases.

Five of the ten individual SMAF scores showed significant differences between tillage practices at the 0- to 5-cm depth, namely MAS, pH, SOC, MBC, and BG. At the 5- to 15-cm depth, with the exception of the P score, PG scored higher than C-D and NT, but in several instances, either C-D or NT was not different from PG. Interestingly, the scores that showed no significant differences showed significant tillage effects using raw, unscored data; therefore, as discussed by Andrews et al. (2004) consideration of inherent soil characteristics resulted in reducing the differences among systems. For P, low SMAF–P scores in individual fields were caused by excess P rather than a P limitation to plant growth. It should be noted that macroaggregation in soils under PG at 0 to 5 cm had a mean SMAF score of 1.00 or the optimum and C-D or NT sites had mean scores of 0.87 and 0.80, respectively, since macroaggregation is extremely important for improving infiltration and reducing erosion and runoff risks (Barthés and Roose, 2002). The SMAF–pH indicator scores were also significantly different at 0 to 5 cm, with PG sites scoring at near-optimum levels with a mean score of 0.96 versus C-D and NT sites, which had lower scores. For SOC at the 0- to 5-cm depth, PG was nearly double that of C-D and NT. At 5 to 15 cm, mean SOC content resulted in a score that was 49% of the optimum for soils in PG, whereas tilled soils were performing at 38% of the optimum. This highlights the slow accumulation of subsurface SOC even in the presence of sustained perennial grass roots. Conant et al. (2001) reported soil C increases resulting from conversion of cropland to grassland but also, to a lesser extent, conversion of native grassland (e.g. Conservation Reserve Program lands) to managed grazing land. Soil organic C scores for tilled systems reflect a loss of C over time, as seen in most Midwestern soils when compared with remnant native vegetation (Collins et al., 1999; David et al., 2009; Karlen et al., 2008). Conversely, soils under PG were either recovering or had not historically been tilled as much as those currently in row crops. Since this was an observational study, inferences regarding causation are not possible, although data from Texas (Stott et al., 2013) support the notion that reestablishment of PG can expedite the recovery of soil quality or health; in this assessment, SOC is strongly tied to SQI. Similar effects were noted by Karlen et al. (2006) for cropping systems comparisons at three Midwestern U.S. locations. These sites also showed improved soil quality for areas that had alfalfa as an integral part of their crop rotation.

Landscape Position Effects

Samples were also sorted by landscape position to compare summit, mid- and toe-slope positions (Table 7). Among the physical indicators, sand, ρ_b and MAS showed significant differences at both depths. Bulk density was significantly greater for summit and mid-slope positions than for toe-slope positions at both 0 to 5cm and 5 to 15 cm. Higher ρ_b values were consistent with greater sand content at those landscape positions, perhaps because of greater long-term erosion. Macroaggregate stability at the toe-slope position was significantly greater than both the summit and mid-slope positions at the 0- to 5-cm depth and greater than the summit position at the 5- to 15-cm depth. This may be related to the weak correlation between MAS and several biological sector indicators, which were also greater in toe-slope areas (0–5 cm: MBC R^2 = 0.25, MAS and BG R^2 = 0.21; 5–15 cm: MBC R^2 = 0.38, C_{min} R^2 = 0.24) (Table 4). Electrical conductivity was the only chemical indicator that exhibited significant landscape position differences, with toe-slope positions having significantly greater values than summit and mid-slope positions at both depths. For biological indicators, means showed the same trends, with significantly greater values at toe-slope positions, where the differences were significant. All nutrient SQIs except for Mn at 5 to 15 cm showed significant differences relating to landscape position and the general trend was: toe-slope > mid-slope > summit, but a few exceptions were present.

The SMAF–ρ_b indicator scores were near-optimum for 0 to 5 cm, with no significant differences among landscape positions; for 5 to 15 cm, mean scores were lower (0.62–0.79) for all positions and toe-slope soils had significantly higher scores than summit and mid-slope soils (Table 7). Once again, ρ_b mean scores were comparable to those found at similar landscape positions in the South Fork Iowa watershed (Stott et al., 2011). For SMAF–pH and SMAF–EC indicator scores, there were no differences among landscape positions at either of the depths and the values were comparable to those reported for the South Fork watershed (Karlen et al., 2008; Stott et al., 2011). Electrical conductivity scores were equal to 1.0 for all soils. The only biological indicator that varied among landscape positions was the SMAF–OC scores in the 0- to 5-cm depth, where samples from the toe-slope had significantly higher scores than those from either the summit or mid-slope positions. Again, the values were comparable to those reported for the South Fork watershed. Soil from the 5- to 15-cm depth had relatively low SOC scores, averaging 0.45. The SMAF–BG indicator scores were also quite low, with means ranging from 0.20 to 0.21 at 0 to 5-cm. The range for individual sample scores at 0 to 5 cm was 0.02 to 0.89. As previously discussed with regard to cropping systems, high scores were obtained from land enrolled in the Conservation Reserve Program or that were planted to perennial grasses. With regard to P and K concentrations, there was only one small but significant difference in scores across landscape positions (P score at 5 to 15 cm), with mean scores being high ($\geq$0.96) and consistent with their landscape counterparts in the South Fork watershed (Stott et al., 2011).

Overall, soils within Cedar Creek watershed were performing at 84% of their potential at 0 to 5 cm, but at only 75% of optimum within the 5- to 15-cm depth increment. Furthermore, there were significant differences among landscape positions, with summit positions being significantly lower than toe-slopes for 0 to 5 cm and both mid- and toe-slope positions for 5 to 15 cm. Once again, these scores were comparable to those reported for the South Fork watershed (Stott et al., 2011). For physical sector SQIs, summit soils had significantly lower scores than other landscape positions and the trends were similar to those for total SQI scores. Chemical and nutrient sector mean scores were uniformly high in the 0- to 5-cm depth: 93 and 98% of the optimum, respectively. Biological sector mean scores were 69 and 55% of the optimum for 0 to 5 and 5 to 15 cm, respectively. For 5 to 15 cm, toe-slope soils had significantly greater means than other landscape positions.

CONCLUSIONS

This study reports the outcomes from a soil quality or soil health assessment conducted within the Cedar Creek watershed in northeastern Indiana. The results demonstrate the following findings: (i) PG systems correlate with enhanced soil quality, (ii) corn-based rotations correlate with diminished soil quality, and (iii) NT has a minimal or neutral short-term effect on soil quality. Perennial grass sites generally had the highest individual SMAF scores as well as high SQI values and corn- and alfalfa-based rotations had the lowest values. Soybean-based cropping systems usually had SMAF scores that fell between high and low values without being significantly different from either. Previously, addition of perennial crops increased N (*Trifolium repens* L.) (Bergkvist et al., 2003) and P (various crops) (Lehmann et al., 2001) availability; increased SOC, MBC, soil mesofauna population and structure (mixed perennial native and non-native species) (DuPont et al., 2014); and increased soil protein and aggregate stability (*Agropyron cristatum* [L.] Gaertn.) (Wright and Anderson, 2000).

When we consider tillage, NT SQI was often indistinguishable from that of C-D systems. Similar SMAF results were found in Michigan and Ohio (Nakajima et al., 2016). This may be because of a variety of reasons, including inherently high SOC, timing of ρ_b measurement (e.g., surface ρ_b may be less immediately after tillage but increase after precipitation and traffic), or the detrimental effect of poorly aerated NT soils on microbial activity. In short, the positive aspects of tillage may outweigh the positive aspects of NT in certain regions over short time scales. Baker et al. (2007) noted that soils in the upper Midwest under NT management without cover crops may still decline in quality, only not as rapidly as soil subjected to more frequent chisel or disk tillage.

The relatively poor performance of biological indicators in soils under row crops, irrespective of tillage management and landscape position, was also observed in the Riesel, TX (Stott et al., 2013) and South Fork, IA watersheds (Karlen et al., 2008; Stott et al., 2011). Similar results were also found in Wisconsin (Jokela et al., 2011) and the loess hills of southwest Iowa (Cambardella et al., 2004). Alternatively, chemical and nutrient indicators in this study were all near optimum. High chemical and nutrient sector SQI scores are indicative that farmers and land managers are very good at managing pH and plant nutrient balances in the soil, though modern agriculture has apparently digressed in its ability to manage the biological components of soil.

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