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Soil quality response to long-term tillage and crop rotation practices

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ABSTRACT

Soil quality is influenced by inherent and anthropogenic factors. This study was conducted to provide multiple groups guidance on how to achieve and maintain improved soil quality/health. Our hypothesis was that tillage intensity was the primary anthropogenic factor degrading soil quality, and our objective was to prove that hypothesis through an intensive 2005 sampling of a central Iowa, USA field study. Chisel plow, disk tillage, moldboard plow, ridge-till and no-till treatments, used for 31 years in a two-year, corn (*Zea mays* L.)/soybean [*Glycine max* (L.) Merr.] (C/S) rotation or for 26 years of continuous corn (CC) production, were evaluated by measuring 23 potential soil quality indicators. Soil samples from 0 to 5- and 5 to 15-cm depth increments were collected from 158 loam or clay loam sampling sites throughout the 10-ha study site. Nine of the indicators were evaluated by depth increment using the Soil Management Assessment Framework (SMAF) which has scoring functions for 13 soil biological, chemical, and physical measurements and can be used to compute individual indicator indices and an overall soil quality index (SQI). Water-stable aggregation (WSA), total organic carbon (TOC), microbial biomass carbon (MBC), and potentially mineralizable nitrogen (PMN) were all significantly lower for the 0 to 5-cm and generally lower for 5 to 15-cm increments after long-term moldboard plowing and its associated secondary tillage operations. This presumably reflected greater physical breakup and oxidation of above- and below-ground plant residues. Bray-P concentrations in moldboard plow plots were also significantly lower at both depth increments. Between soil texture groups, significant differences were found for WSA, Bray-P, TOC and MBC at both depth increments and for both cropping systems. When combined into an overall SQI, both soil texture groups were functioning at 82–85% of their potential at 0–5-cm and at 75% of their potential at the 5–15-cm depth. Our hypothesis that moldboard plowing would have the greatest negative effect on soil quality indicators was verified. Based on this assessment, we recommend that to achieve and maintain good soil health, producers should strive to adopt less aggressive tillage practices.

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1. Introduction

Soil quality/health is a product of inherent (parent material, climate, and topography) and anthropogenic (tillage and crop rotation) interactions (Karlen et al., 1997). Tillage, which evolved as part of anthropogenic soil management, gradually became an integral part of crop production systems such that by 4000 years before present (BP), wooden plows drawn by oxen were used to scratch the soil surface in Europe, China, and many other regions. However, plows that actually inverted the soil were not developed

until the 17th century. European advancements during the 18th century resulted in the moldboard plow which turned the soil by 135° and significantly improved weed control (Derpsch, 1998). This was of tremendous importance to many Europeans and especially the Germans because with soil inversion, they could overcome quackgrass (*Agropyron repens*) infestations that had become nearly impossible to control.

Presumably the European experience with moldboard plowing contributed to its widespread use when immigrants from those regions needed to break the prairie as they settled the U.S. Midwest (Karlen et al., 2010). Unfortunately by the mid 1930s, plowing had caused 40% of the land area in Iowa to lose 50–70% of its surface soil, which was often deposited in rivers and lakes as silt (Chase, 1936). Opportunities to slow this natural resource degradation by decreasing the intensity of tillage became scientifically feasible following World War II. Development of plant growth regulators (i.e., herbicides) and improved fertilizer management strategies

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made it feasible to grow crops with less and less tillage (Phillips and Phillips, 1984).

The need for information on less intensive tillage systems for Midwestern USA soils was a primary reason for initiating tillage and crop rotation studies at this research site in 1975 (Erbach, 1982). To quantify long-term effects of those practices after 31 years of known management (Karlen et al., 2013), an intensive sampling and soil quality indicator assessment was conducted to test our hypothesis that intensive tillage practices were degrading soil quality/health.

To quantify long-term tillage effects, the Soil Management Assessment Framework (SMAF) developed by Andrews et al. (2004) was used as a soil quality assessment tool. The SMAF uses a 3-step process to assess soil quality. This includes indicator selection, indicator interpretation, and integration into an overall soil quality index or SQI. Soil taxonomy provides the foundation for each assessment based on soil suborder characteristics. Assessment values are generally expressed as a fraction or percentage of full performance for soil functions such as crop productivity, nutrient cycling, or environmental filtering and buffering. Currently, the SMAF has scoring curves or interpretation algorithms for 13 indicators: water-stable macroaggregation (WSA), plant-available water (PAW), water-filled pore space (WFPS), bulk density (BD), electrical conductivity (EC), pH, sodium adsorption ratio (SAR), extractable P and K, soil organic carbon (SOC), microbial biomass carbon (MBC), potentially mineralizable N (PMN), and β -glucosidase (BG) activity (Andrews et al., 2004; Wienhold et al., 2009; Stott et al., 2010).

The SMAF has been used in the U.S. and abroad to evaluate near-surface (0–5 and 5–15 cm) soil properties and processes (e.g. Fernandez-Ugale et al., 2009; Imaz et al., 2010; Jokela et al., 2009; Karlen et al., 2006, 2011; Liebig et al., 2006; Stott et al., 2011; Wienhold et al., 2006; Zobeck et al., 2008). The unique aspect of this study is the longevity of the tillage and crop rotation treatments and the intensive analysis of soil samples representing two important texture groups (loam and clay loam). We

hypothesized that intensive tillage (i.e., moldboard plowing) and acidification due to higher N fertilizer applications for continuous corn (CC) would have the most notable effects on soil quality. We also hypothesized that the differences would be more detectable within loam sampling sites because they are located at a slightly higher elevation (~2–3 m) and are often more eroded than the clay loam sites. We tested these hypotheses by intensively sampling 40, 0.3 ha plots where five tillage practices had been evaluated for C/S or CC rotations for 31 or 26 years, respectively.

2. Methods and materials

2.1. Site characteristics and general experimental design

The long-term tillage and crop rotation study for which this soil quality/soil health assessment was conducted was initiated in 1975 (Erbach, 1982) at the Iowa State University (ISU) Agronomy/Ag Engineering Research and Education Center (AAEREC) in Boone County, IA (latitude 42°01' N, longitude 93°45' W). As summarized by Karlen et al. (2013) there initially were eight “replicates” of each tillage system with four each managed in each phase of a corn and soybean rotation. Each tillage plot was 33 m wide and 91 m long except on the northwest and southeast corners of this 10-ha research site, where grass waterways (installed to capture and divert surface runoff from the research site) resulted in slightly shorter plots (Fig. 1). The tillage systems were: (1) slot plant on ridges which was eventually transitioned to a no-till operation; (2) spring disk; (3) till plant (ridge tillage) where surface soil to a depth of ~5–8 cm is “thrown off” during planting and then the ridges are later rebuilt through cultivation; (4) fall moldboard plowing; and (5) fall chisel plowing. From 1976 through 1980, the plots were managed in an alternating corn and soybean rotation. Starting in 1979 and continuing through 2006, the four replicates in the south half of the site (Fig. 1) were used for continuous corn (CC) production, while the north half was maintained in the corn/soybean (C/S) rotation with each crop occurring every other year.

Fig. 1. Elevation, soil series, and plot layout for the long-term tillage evaluations on the ISU Agronomy/Agricultural Engineering Research Center near Boone, Iowa, USA. The bottom half was in continuous corn (CC) from 1979 through 2005, while the top half was in a corn and soybean (C/S) rotation from 1975 through 2005. The points represent the 2005 soil sampling sites.

Soils at this site are classified by the USDA Soil Survey Staff (2010) as Clarion loam (Fine-loamy, mixed, superactive, mesic Typic Hapludolls), Canisteo clay loam (Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls), and Webster silty clay loam (Fine-loamy, mixed, superactive, mesic Typic Endoaquolls). Composite soil samples consisting of 12 soil cores were collected at four locations within each plot using a 32-mm diameter soil probe following the 2005 grain harvest. Soil cores were separated into two depth increments, 0–5 cm and 5–15 cm and combined by depth increment into four composite samples per plot. A fixed sampling pattern was used with each composite sample being taken within a 3 m diameter circle 18-, 37-, 49-, and 73-m from the west edge of each plot (Fig. 1). Both clay loam soil series were pooled into a single group for comparison with samples from loam sites. This approach resulted in 61 sampling sites classified as loam and 97 classified as clay loam.

2.2. A summary of long-term agronomic practices

Long-term soil and crop management records, crop yields, profile soil-test P and K and net returns for the five systems were summarized by Karlen et al. (2013). In general, all management decisions reflected best management practices associated with establishment (1975 to 1980), maintenance (1981 through 2002) and recovery/intensification (2003 through 2006) phases for this experiment. Commercially available corn and soybean cultivars were planted in 76 cm rows between late April and early June each year. Total fertilizer N-P-K application for the C/S rotation was 2956–423–852 kg ha⁻¹, respectively, while for the CC field, a total of 5022–280–508 kg ha⁻¹, respectively, was applied (Karlen et al., 2013).

2.3. Soil quality assessment

To assess long-term tillage and cropping system effects on soil quality, each composite soil sample was placed in a plastic bag, stored on ice until it could be transported to the lab, and then refrigerated at 4 °C until further processing. The field-moist samples were weighed and mixed before taking a 100 g subsample and drying it at 105 °C to determine soil water content. The total field-moist weight per composite sample was adjusted to a dry weight and divided by the volume associated with the 12 soil cores to estimate bulk density (BD) (Arshad et al., 1996; Blake and Hartge, 1986) for the 0–5-cm and 5–15-cm depths. The remaining field-moist soil sample was passed through an 8-mm screen, air-dried, and then crushed to pass a 2-mm sieve. Sub-samples from each depth increment were analyzed for soil pH (Watson and Brown, 1998) and electrical conductivity (EC) (Whitney, 1998) using a 1:1 soil to water ratio. A second sub-sample was extracted with 2 M KCl and analyzed for ammonium (NH₄-N) and nitrate (NO₃-N) concentrations using flow injection analysis (Lachat QC 800; Loveland, CO). A third set of sub-samples was submitted to a commercial soil-testing laboratory and analyzed for Bray-1 extractable P (Bray P) (Bray and Kurtz, 1945) and ammonium-acetate (NH₄OAc) exchangeable (Ex-) K, Ca, Mg and Na concentrations (Warneke and Brown, 1998).

A fourth sub-sample was created by placing approximately 30 g of air-dry soil in a glass jar with steel rods, closing the jar and placing the sample on a roller belt for approximately 24 h in order to pulverize the soil before analyzing it for total carbon (TC) and total nitrogen (TN) by dry combustion. Based on soil pH, neither depth increment appeared to have sufficient inorganic carbon (IC) to warrant volumetric measurement (Wagner et al., 1998), so TC and total organic carbon (TOC) were assumed to be the same.

Water-stable aggregation was determined using a modified Yoder (1936) wet-sieving apparatus designed to mechanically

agitate a stack of five-sieves to separate macroaggregates into five size classes (4–8, 2–4, 1–2, 0.5–1 and 0.25–0.50 mm). A 100-g sample of air-dried, 8 mm sieved soil was placed on top of the stack of sieves and the sieve stack was agitated for 5 min at 125 rpm with a vertical stroke length of 1.8 cm. Wet aggregate stability (percent macro-aggregation) was calculated by summing aggregate mass for all classes greater than 0.25-mm, dividing by the total soil mass, and multiplying by 100.

Microbial biomass C was measured by fumigation and direct extraction with 0.5 M K₂SO₄ on 8-mm-sieved field-moist samples (Vance et al., 1987). Organic C in the fumigated and non-fumigated extracts was measured using a Dohrmann DC-180 carbon analyzer (Rosemount Analytical Services, Santa Clara, CA) and biomass C was calculated using the correction factor ($k = 0.33$) of Sparling and West (1988). Particulate organic matter (POM) was determined as described by Cambardella and Elliott (1992). Nitrogen mineralization potential was quantified after 28-day aerobic incubation using a modification of Keeney and Bremner's (1967) method as described by Drinkwater et al. (1996).

2.4. Statistical analyses

The data were analyzed by cropping system and depth increment using a SAS General Linear Model (GLM) to determine tillage system, textural group, replicate and tillage system by textural group interactions (SAS Institute, 1990). Least significant difference (LSD) values were calculated to separate means for factors that had F values of $P \leq 0.10$. A 10% significance level was chosen because inherent variability that can be blocked in small replicated plot studies often masks field-scale differences important to land managers. Mean values for nine of the indicators (Tables 1 and 2) were used for SMAF analyses to determine how tillage affected soil quality for the two textural groups and crop rotations. Physical effects are represented by WSA and BD, while chemical effects are represented by pH, EC, Bray-P and Ex-K, and biological effects by TOC, MBC, and PMN. This approach is consistent with the general SMAF guidelines which recommend using a minimum of five indicators with at least one each representing anticipated soil biological, chemical, and physical property or process responses (Karlen et al., 2008). The indicators were scored by transforming mean measured values into 0–1 values using the SMAF scoring curves. Those curves account for organic matter, texture, climate, slope, region, mineralogy, weathering class, crop, sampling time, and analytical method effects on the various threshold values (Andrews et al., 2004; Wienhold et al., 2009; Stott et al., 2010). The indicator scores were examined individually and as an overall soil quality index (SQI) to determine how the nine parameters were affected by tillage, crop rotation, and soil series. No additional statistical analyses were run on the SMAF scores since they were calculated using mean values for the selected indicators.

3. Results and discussion

3.1. Tillage system differences for SMAF indicator means

Measurements of WSA at both depth increments (Table 1) showed lower values for the moldboard plow treatment indicating a less stable soil condition and a surface that would be more vulnerable to wind and water erosion. Differences in BD within the 0–5-cm increment were small but the moldboard plow treatment did have significantly higher values in both fields, presumably because the number of tillage operations (*i.e.*, plowing, 1–3 disk operations, and 1–2 field cultivations) resulted in greater break up, incorporation, and oxidation of above- and below-ground plant residues during the course of this study. Therefore from a physical

Table 1

Tillage system effects on nine indicators used in a SMAF analysis of soil quality for two depth increments following 26 years of continuous corn (CC) or 31 years in a corn-soybean (C/S) rotation on glacial till soils in central Iowa.

Tillage system	WSA ^a (g kg ⁻¹)	BD (g cm ⁻³)	pH	EC (μs cm ⁻¹)	Bray P (mg kg ⁻¹)	Ex-K (mg kg ⁻¹)	TOC (g kg ⁻¹)	MBC (μg g ⁻¹)	PMN (mg g ⁻¹)
CC: 0–5 cm depth									
Moldboard plow	298	1.2	6.5	102	17	110	20	179	26
Chisel plow	383	1.1	6.4	106	39	131	25	302	52
Spring disk	410	1.0	6.8	111	42	162	28	481	54
Ridge-tillage	456	1.1	6.4	112	35	135	29	466	66
No-tillage	483	1.0	6.6	109	36	171	30	504	71
LSD _(0.1)	31	0.1	0.2	4	6	17	2	61	12
CC: 5–15 cm depth									
Moldboard plow	352	1.2	6.7	103	15	79	20	147	29
Chisel plow	443	1.2	6.4	102	30	84	24	178	35
Spring disk	448	1.1	6.7	104	27	100	24	247	37
Ridge-tillage	447	1.2	6.4	101	25	84	22	194	32
No-tillage	489	1.1	6.8	101	25	95	24	240	37
LSD _(0.1)	39	NS ^b	0.2	2	5	11	2	42	6
C/S: 0–5 cm depth									
Moldboard plow	280	1.3	6.4	104	19	110	21	247	20
Chisel plow	307	1.0	6.1	102	28	124	25	359	43
Spring disk	382	1.0	6.2	106	33	131	28	410	42
Ridge-tillage	352	1.1	6.5	109	37	130	27	412	54
No-tillage	386	1.0	6.3	104	35	127	28	495	47
LSD _(0.1)	33	0.1	0.2	3	5	15	2	53	9
C/S: 5–15 cm depth									
Moldboard plow	330	1.1	6.5	101	18	98	21	217	24
Chisel plow	363	1.1	6.1	101	22	101	23	247	28
Spring disk	426	1.1	6.1	102	23	97	24	258	27
Ridge-tillage	382	1.1	6.1	101	25	102	23	186	24
No-tillage	410	1.1	6.4	102	25	93	22	265	23
LSD _(0.1)	48	NS	0.2	NS	5	10	2	38	NS

^a WSA: water stable macroaggregate fraction; BD: bulk density; pH: acidity/alkalinity; EC: electrical conductivity; Bray P: extractable P using the Bray P1 reagent; Ex-K: NH₄OAc exchangeable K; TOC: total organic carbon; MBC: microbial biomass carbon; PMN: potentially mineralizable nitrogen.

^b NS: indicates no statistical significance among mean values at $P \leq 0.1$.

Table 2

Soil texture group means for the nine indicators used in a SMAF analysis of soil quality for two depth increments following 26 years of continuous corn (CC) or 31 years in a corn-soybean (C/S) rotation on glacial till derived soils in central Iowa.

Texture group	WSA ^a (g kg ⁻¹)	BD (g cm ⁻³)	pH	EC (μs cm ⁻¹)	Bray P (mg kg ⁻¹)	Ex-K (mg kg ⁻¹)	TOC (g kg ⁻¹)	MBC (μg g ⁻¹)	PMN (mg g ⁻¹)
CC: 0–5 cm depth									
Loam	389	1.1	6.7	106	26	140	24	347	56
Clay loam	418	1.0	6.4	109	39	144	28	414	53
LSD _(0.1)	20	0.1	0.2	3	4	NS ^b	1	40	NS
CC: 5–15 cm depth									
Loam	418	1.1	6.7	102	19	86	21	185	34
Clay loam	448	1.2	6.5	102	28	90	24	213	34
LSD _(0.1)	25	NS	0.2	NS	3	NS	1	27	NS
C/S: 0–5 cm depth									
Loam	296	1.2	6.4	104	23	110	21	302	43
Clay loam	369	1.0	6.3	105	35	133	28	434	41
LSD _(0.1)	22	0.1	NS	NS	3	10	2	34	NS
C/S: 5–15 cm depth									
Loam	314	1.1	6.2	101	18	100	19	188	25
Clay loam	423	1.1	6.3	102	26	98	24	263	25
LSD _(0.1)	31	0.03	NS	NS	3	NS	1	25	NS

^a WSA: water stable macroaggregate fraction; BD: bulk density; pH: acidity/alkalinity; EC: electrical conductivity; Bray P: extractable P using the Bray P1 reagent; Ex-K: NH₄OAc exchangeable K; TOC: total organic carbon; MBC: microbial biomass carbon; PMN: potentially mineralizable nitrogen.

^b NS: indicates no statistical significance among mean values at $P \leq 0.1$.

soil quality indicator perspective, both WSA and BD indicate that the more aggressive tillage practices had a negative effect.

Among the chemical indicators (Table 1) of soil quality (pH, EC, Bray-P and Ex-K) there were statistical differences among tillage treatments for pH and EC, but differences among means were small and would have virtually no effect on crop emergence, growth or productivity. Bray-P was significantly lower in both fields and at both depth increments in the moldboard plow treatments and

except for the 5–15-cm depth increment Ex-K was also significantly lower after more than 30 years of moldboard plowing. Based on ISU soil test interpretations (Sawyer et al., 2011), the Bray-P values were still in the optimum range for all tillage treatments, but as discussed by Karlen et al. (2013) Ex-K levels were low and perhaps yield limiting.

Examining the carbon-based biological indicators (Table 1), we see that at both the 0–5- and 5–15-cm sampling depths,

moldboard plowing resulted in the lowest TOC concentrations after 26 years of CC or 31 years in a C/S rotation. The two microbial-mediated indicators (MBC and PMN) also show the lowest values at both sampling depth for the moldboard plowing under CC and at the 0–5-cm depth in the C/S field. Some may argue that since only the 0–5- and 5–15-cm depth increments were analyzed, it is possible that lower TOC, MBC, and PMN values at those depths simply reflects burying of crop residue below 15 cm through the moldboard plowing operation. However, based on similar studies by Varvel and Wilhelm (2011) that showed greater soil N and SOC levels deep in the profile beneath less aggressive tillage practices and unpublished profile carbon data from this site, we conclude that a substantial portion of the carbon added annually through photosynthesis was lost when tillage practices were aggressive.

Data in Table 1 also show a stratification effect for all three biological indicators evident when comparing sampling depths. Averaging measurements for the two fields shows mean values of 26 vs. 23 g kg⁻¹ for TOC, 386 vs. 218 µg g⁻¹ for MBC, and 48 vs. 30 mg g⁻¹ for PMN within the 0–5- and 5–15-cm increments, respectively. Furthermore, within both the CC and C/S fields, all three indicators are higher in long-term no-tillage treatments than all other tillage treatments in the 0–5-cm increment, but among the lowest values within the 5–15-cm increment.

3.2. Soil texture group differences among SMAF indicator means

Mean surface soil quality indicator values for the two soil texture groups within both fields are presented in Table 2. For WSA, significant differences were found in both fields and at both depth increments, with the more sloping, loam sites having lower WSA values than the relatively flat, clay loam sites. Texture is an obvious contributing factor to these differences, but of more importance for long-term soil security, lower values for loam soils, which are located at a slightly higher elevation, mean they are also

more vulnerable to wind and water erosion. A comparison between the two fields shows that CC increased WSA at both depth increments and in both texture groups when compared to the adjacent C/S field. Presumably this also reflected greater carbon inputs with CC, as soybean is known to be a “low residue” crop and thus more prone to creating more erosive soil conditions (Alberts et al., 1985). For BD, there were statistically significant differences between the two soil texture groups, but they were very small and would have no measureable impact on productivity of either crop.

Among the chemical indicators of soil quality/health (Table 2), Bray P showed the most consistent differences due to textural group with the loam sites being lower than the clay loam sites. However, the concentrations at both depths were sufficient for good corn and soybean production. Ex-K showed significant differences between the two textural groups within the C/S field, but more notably for the site was that except for the loam sites in the CC field, all Ex-K levels were low to very low based on ISU soil-test guidelines (Sawyer et al., 2011). Soil pH and EC showed few significant differences between texture groups, with none that would be expected to affect crop growth and development.

Among biological soil quality indicators, TOC and MBC concentrations were significantly lower in the loam samples than in clay loam soils (Table 2), but PMN levels showed no significant differences between soil texture groups. This was a bit unexpected since C and N pools often show similar patterns. We attribute this to variability and perhaps the presence of N not associated with the TOC or MBC fractions.

3.3. SMAF analysis of tillage system and SMU effects

The SMAF scores for each of the nine indicators as well as an overall SQI for comparing the five tillage systems and two soil texture groups within the long-term CC and C/S fields are presented in Tables 3 and 4, respectively. Those data show that

Table 3
SMAF soil quality indicator scores and the overall soil quality index (SQI) values as affected by tillage system and texture group at two depth increments in glacial till derived soils after 26 years of continuous corn (CC) in central Iowa.

Tillage	Texture group	WSA ^a	BD	pH	EC	Bray P	Ex-K	TOC	MBC	PMN	SQI
0–5 cm											
Plow	Loam	0.96	0.99	0.98	0.62	1.00	0.79	0.67	0.98	1.00	0.89
Chisel	Loam	0.90	0.99	1.00	0.61	0.99	0.75	0.53	0.62	1.00	0.82
Disk	Loam	0.90	0.99	0.99	0.65	1.00	0.85	0.74	0.98	1.00	0.90
Ridge-till	Loam	0.94	0.99	1.00	0.65	1.00	0.78	0.84	0.99	1.00	0.91
No-till	Loam	0.71	0.99	1.00	0.59	0.97	0.69	0.45	0.31	0.94	0.74
Average		0.88	0.99	0.99	0.62	0.99	0.77	0.65	0.77	0.99	0.85
Plow	Clay loam	0.94	0.99	1.00	0.66	1.00	1.00	0.82	0.97	1.00	0.93
Chisel	Clay loam	0.79	0.96	1.00	0.62	1.00	0.89	0.55	0.63	1.00	0.83
Disk	Clay loam	0.85	0.99	1.00	0.66	1.00	0.93	0.65	0.96	1.00	0.89
Ridge-till	Clay loam	0.90	0.99	1.00	0.66	1.00	0.90	0.65	0.90	1.00	0.89
No-till	Clay loam	0.66	0.97	1.00	0.61	0.98	0.83	0.32	0.22	0.87	0.72
Average		0.83	0.98	1.00	0.64	1.00	0.91	0.60	0.74	0.97	0.85
5–15 cm											
Plow	Loam	0.93	0.99	0.98	0.59	0.98	0.56	0.38	0.33	0.99	0.75
Chisel	Loam	0.83	0.99	1.00	0.60	0.97	0.56	0.42	0.20	1.00	0.73
Disk	Loam	0.94	0.99	0.99	0.61	1.00	0.68	0.60	0.66	1.00	0.83
Ridge-till	Loam	0.97	0.99	1.00	0.59	1.00	0.55	0.67	0.23	0.99	0.78
No-till	Loam	0.93	0.99	1.00	0.61	0.96	0.56	0.44	0.24	0.96	0.74
Average		0.92	0.99	0.99	0.60	0.98	0.58	0.50	0.33	0.99	0.77
Plow	Clay loam	1.00	0.96	1.00	0.59	1.00	0.83	0.64	0.55	1.00	0.84
Chisel	Clay loam	0.73	0.87	1.00	0.60	1.00	0.74	0.54	0.24	0.99	0.75
Disk	Clay loam	0.90	0.89	1.00	0.61	1.00	0.75	0.52	0.34	0.99	0.78
Ridge-till	Clay loam	0.88	0.85	1.00	0.59	1.00	0.73	0.38	0.24	0.97	0.74
No-till	Clay loam	0.89	0.87	1.00	0.60	0.96	0.71	0.31	0.14	0.95	0.71
Average		0.88	0.89	1.00	0.60	0.99	0.75	0.48	0.30	0.98	0.76

^a WSA: water stable macroaggregate fraction; BD: bulk density; pH: acidity/alkalinity; EC: electrical conductivity; Bray-P: extractable phosphorus; Ex-K: exchangeable potassium; TOC: total organic carbon; MBC: microbial biomass carbon; PMN: potentially mineralizable nitrogen; SQI: soil quality index.

Table 4

SMAF soil quality indicator scores and the overall soil quality index (SQI) values as affected by tillage system and soil series at two depth increments in glacial till derived soils after 31 years of a corn-soybean rotation (C/S) in central Iowa.

Tillage	Texture group	WSA ^a	BD	pH	EC	Bray P	Ex-K	TOC	MBC	PMN	SQI
Plow	Loam	0.81	0.99	1.00	0.61	0.99	0.70	0.55	0.93	1.00	0.84
Chisel	Loam	0.71	0.99	1.00	0.60	1.00	0.70	0.52	0.86	1.00	0.82
Disk	Loam	0.71	0.99	1.00	0.63	1.00	0.69	0.60	0.82	1.00	0.83
Ridge-till	Loam	0.81	0.99	1.00	0.64	1.00	0.69	0.52	0.81	1.00	0.83
No-till	Loam	0.64	0.95	1.00	0.59	0.97	0.69	0.42	0.59	0.82	0.74
Average		0.74	0.98	1.00	0.61	0.99	0.69	0.52	0.80	0.96	0.81
Plow	Clay loam	0.84	0.99	1.00	0.61	1.00	0.90	0.68	0.97	1.00	0.89
Chisel	Clay loam	0.72	0.99	1.00	0.61	1.00	0.91	0.63	0.82	0.99	0.85
Disk	Clay loam	0.84	0.99	1.00	0.62	1.00	0.90	0.63	0.86	1.00	0.87
Ridge-till	Clay loam	0.90	0.99	1.00	0.64	1.00	0.91	0.69	0.92	1.00	0.90
No-till	Clay loam	0.63	0.53	1.00	0.62	0.98	0.84	0.36	0.39	0.51	0.65
Average		0.78	0.90	1.00	0.62	1.00	0.89	0.60	0.79	0.90	0.83
Plow	Loam	0.83	0.99	1.00	0.60	0.97	0.65	0.37	0.33	0.58	0.70
Chisel	Loam	0.78	0.99	1.00	0.59	0.98	0.65	0.42	0.48	0.99	0.76
Disk	Loam	0.66	0.99	1.00	0.59	0.97	0.67	0.43	0.34	0.82	0.72
Ridge-till	Loam	0.83	0.99	1.00	0.59	0.97	0.68	0.37	0.24	0.77	0.71
No-till	Loam	0.71	0.99	1.00	0.59	0.97	0.65	0.44	0.47	0.92	0.75
Average		0.76	0.99	1.00	0.59	0.97	0.66	0.41	0.37	0.81	0.73
Plow	Clay loam	0.88	0.96	1.00	0.60	1.00	0.75	0.46	0.54	0.84	0.78
Chisel	Clay loam	0.85	0.96	1.00	0.59	1.00	0.82	0.55	0.27	0.80	0.76
Disk	Clay loam	0.90	0.95	1.00	0.60	1.00	0.78	0.49	0.46	0.92	0.79
Ridge-till	Clay loam	0.82	0.99	1.00	0.59	1.00	0.80	0.59	0.26	0.87	0.76
No-till	Clay loam	0.77	0.94	1.00	0.59	0.98	0.78	0.38	0.30	0.75	0.72
Average		0.84	0.96	1.00	0.60	1.00	0.79	0.47	0.37	0.84	0.76

^a WSA: water stable macroaggregate fraction; BD: bulk density; pH: acidity/alkalinity; EC: electrical conductivity; Bray-P: extractable phosphorus; Ex-K: exchangeable potassium; TOC: total organic carbon; MBC: microbial biomass carbon; PMN: potentially mineralizable nitrogen; SQI: soil quality index.

following 26 years of CC, the PMN, pH, and Bray P values all achieved SMAF scores of 1.0 (Table 3) indicating that for crop productivity, they were functioning at their full potential within both depth increments. Bulk density scores were also approximately 1.0 indicating no root-limiting conditions, except for the 5–15 cm depth within the clay loam sites where the average score was 0.89. That would indicate a slight (~10%) reduction from full potential for crop production in those areas. WSA scores were generally the next lowest, ranging from 0.83 to 0.92 (i.e., 83–92% of full potential) and being about 5% higher in the 5–15 cm increment for both soil texture groups. EC scores for all five tillage systems, both texture groups, and both sampling depths were all between 0.59 and 0.66. These chemical soil quality indicator scores were somewhat lower than expected for Midwestern soils, but probably reflected high Ca and Mg concentrations as discussed in section 3.4. The Ex-K scores after long-term CC reflect low concentrations in the 5–15 cm increment as discussed previously (Tables 1 and 2) and were lowest for the more sloping Clarion loam than clay loam sites. The final two biological indicators of soil quality/health, TOC and MBC had the lowest SMAF scores in the CC field, especially within the 5 to 15 cm depth increment due to an apparent depletion of soil organic matter when compared to what is expected based on the soil-forming factors and inherent condition (USDA-SCS, 1981) of soils in this area.

The SMAF scores for samples collected following a 31-year C/S rotation are shown in Table 4. Soil pH, Bray P, and BD scores for the five tillage systems, both texture groups and both depth increments were generally between 0.9 and 1.0 in this field indicating those factors were fully functioning with regard to crop production. The PMN indicator in the 0–5 cm depth increment also averaged 0.90 and 0.96 for the loam and clay loam sampling sites, respectively, but within the 5–15 cm depth increment, the average scores for that biological indicator decreased to 0.81 and 0.84, respectively, indicating less potentially available N than

would normally be expected at that depth for these soils. WSA and Ex-K scores were the next lowest at this site, ranging from 0.74 to 0.84 or 0.66 to 0.89, respectively. For both of these indicators, average scores for the five tillage systems within clay loam sites were slightly higher than at loam sites, presumably reflecting the higher clay content that would affect both aggregate stability (WSA) and cation exchange capacity (CEC). As discussed for the CC field, EC scores once again averaged 0.6 for both texture groups and depth increments, presumably reflecting the high Ca and Mg concentrations in these soils. Also, as noted for the CC field, the final two biological soil quality indicators, TOC and MBC had the lowest SMAF scores with averages of 0.56 and 0.44 or 0.80 and 0.37 within the 0–5- and 5–15-cm depth increments, respectively. Again, we suggest these low scores reflect a depletion of soil organic matter when compared to inherent levels expected for these soils.

The average SQI for the five tillage systems within the 0–5 cm sampling depth for both texture groups in the CC field (Table 3) was 0.85, indicating soils at that depth were functioning at 85% of their potential, but within the 5–15 cm depth increment, both texture groups were functioning at just over 75% of their potential. The lower SQI value for the 5–15 cm depth increment was primarily due to very low TOC and MBC scores, although Ex-K and BD scores were also lower at that depth. Within the C/S field (Table 4), the average SQI for the five tillage treatments and two soil texture groups showed that following 31 years of a C/S rotation, the loam and clay loam soils were functioning at 82 and 74% of their anticipated potential for crop production within the 0–5- and 5–15-cm depth increments, respectively.

3.4. Non-SMAF indicator evaluations

In addition to the nine SMAF indicators that were measured and evaluated, 14 other soil measurements were made on samples from both depth increments at all 158 sites (Fig. 1). Those analyses

Table 5

Cation exchange capacity (CEC) and base saturation within the 0–5- and 5–15-cm depth increments of glacial till derived soils as affected by crop rotation and long-term tillage treatments in central Iowa after 26 years of continuous corn (CC) or 31 years of a corn-soybean (C/S) rotation in central Iowa.

Tillage	CEC (cmol kg ⁻¹)	Base saturation				
		Total (g kg ⁻¹)	K (g kg ⁻¹)	Ca (g kg ⁻¹)	Mg (g kg ⁻¹)	H (g kg ⁻¹)
CC: 0–5 cm depth						
Moldboard plow	18	902	15	702	184	98
Chisel plow	20	889	17	699	173	111
Spring disk	19	985	22	812	150	15
Ridge-tillage	18	889	19	690	180	111
No-tillage	19	902	24	692	186	98
LSD _(0.1)	NS ^a	66	3	57	18	66
CC: 5–15 cm depth						
Moldboard plow	16	940	12	727	201	60
Chisel plow	19	875	12	698	165	125
Spring disk	17	961	15	781	165	39
Ridge-tillage	20	859	11	671	176	141
No-tillage	18	950	14	754	182	50
LSD _(0.1)	2	64	2	50	22	64
C/S: 0–5 cm depth						
Moldboard plow	17	904	16	702	186	96
Chisel plow	20	832	17	692	174	167
Spring disk	20	847	16	652	178	153
Ridge-tillage	18	879	18	682	179	121
No-tillage	19	866	17	658	191	134
LSD _(0.1)	2	56	2	49	18	56
C/S: 5–15 cm depth						
Moldboard plow	16	926	16	722	188	74
Chisel plow	18	839	14	664	161	161
Spring disk	19	833	14	641	178	167
Ridge-tillage	19	812	14	639	158	188
No-tillage	18	864	13	681	170	136
LSD _(0.1)	2	70	2	55	20	70

^a NS: indicates no statistical significance among mean values at $P \leq 0.1$.

included: total nitrogen (TN), nitrate-N (NO₃-N), ammonium-N (NH₄-N), particulate organic matter carbon (POM-C), extractable sulfur (S), NH₄OAc exchangeable Ca, Mg, and Na (Ex-Ca, Ex-Mg, and Ex-Na, respectively), cation exchange capacity (CEC), percent base saturation (BS) and percent K, Ca, Mg, and H saturation.

Probability levels ($P > F$) from an analysis of variance (ANOVA) for all 23 indicators at both sampling depths are presented in [Appendix Tables A.1 and A.2](#) for the CC and C/S fields, respectively.

There were several statistically significant ($P \leq 0.1$) tillage, texture group, and replicate main effects, but the only tillage by texture group interactions that were statistically significant were for pH, Bray P and MBC at the 0–5-cm depth and for extractable S at the 5–15-cm depth.

Mean CEC, total base saturation, and saturation percentages for K, Ca, Mg, and H are presented in [Tables 5 and 6](#). Although there are currently no SMAF scoring curves for these indicators, they were

Table 6

Soil texture group effects on cation exchange capacity (CEC) and base saturation within the 0–5- and 5–15-cm depth increments of glacial till derived soils following 26 years of continuous corn (CC) or 31 years of a corn-soybean (C/S) rotation in central Iowa.

Texture group	CEC (cmol kg ⁻¹)	Base saturation				
		Total (g kg ⁻¹)	K (g kg ⁻¹)	Ca (g kg ⁻¹)	Mg (g kg ⁻¹)	H (g kg ⁻¹)
CC: 0–5 cm depth						
Loam	17	942	21	748	173	58
Clay loam	20	895	19	701	175	105
LSD _(0.1)	1	42	NS ^a	37	NS	42
CC: 5–15 cm depth						
Loam	16	946	14	755	177	54
Clay loam	19	896	12	707	178	104
LSD _(0.1)	1	NS	1	NS	NS	NS
C/S: 0–5 cm depth						
Loam	16	884	17	692	174	116
Clay loam	20	855	17	652	186	145
LSD _(0.1)	1	NS	NS	32	NS	NS
C/S: 5–15 cm depth						
Loam	16	829	16	652	161	171
Clay loam	19	870	13	680	177	130
LSD _(0.1)	1	NS	1	NS	NS	NS

^a NS: indicates no statistical significance among mean values at $P \leq 0.1$.

Table 7

Tillage system effects on additional mean soil quality indicator values for the 0–5- and 5–15-cm depth increments in soils derived from glacial till after 26 years of continuous corn (CC) or 31 years of a corn-soybean (C/S) rotation in central Iowa.

Tillage system	Ex-Ca ^a	Ex-Mg (mg kg ⁻¹)	Ex-Na (mg kg ⁻¹)	S (mg kg ⁻¹)	TN (mg kg ⁻¹)	NO ₃ -N (mg kg ⁻¹)	NH ₄ -N (mg kg ⁻¹)	POM-C (mg g ⁻¹)
CC: 0–5 cm depth								
Moldboard plow	2546	401	34	1.8	1.7	8	0.9	2.7
Chisel plow	2735	402	32	2.1	2.0	14	2.1	4.8
Spring disk	3075	343	32	1.8	2.2	16	1.2	7.4
Ridge-tillage	2519	398	30	2.1	2.3	19	3.9	8.1
No-tillage	2546	412	31	2.9	2.5	17	4.0	7.5
LSD _(0.1)	285	46	2	0.6	0.1	3	NS ^b	1.4
CC: 5–15 cm depth								
Moldboard plow	2346	390	34	2.6	1.6	6	0.8	1.7
Chisel plow	2655	372	33	1.8	1.9	8	1.0	2.5
Spring disk	2707	340	32	1.7	1.9	8	1.3	3.5
Ridge-tillage	2584	404	33	2.5	1.8	6	2.9	1.9
No-tillage	2670	392	34	1.9	1.9	7	1.4	1.9
LSD _(0.1)	267	43	NS	0.8	0.2	1	1.9	1.2
C/S: 0–5 cm depth								
Moldboard plow	2485	396	37	2.7	1.7	7	1.3	2.9
Chisel plow	2489	404	35	2.7	2.0	11	0.7	5.1
Spring disk	2607	428	34	2.6	2.2	14	0.8	6.2
Ridge-tillage	2509	393	37	2.2	2.2	13	1.8	6.8
No-tillage	2449	427	34	2.5	2.3	12	1.3	6.7
LSD _(0.1)	NS	NS	2	NS	0.2	2	0.7	1.1
C/S: 5–15 cm depth								
Moldboard plow	2348	367	35	2.5	1.7	6	1.4	3.4
Chisel plow	2394	350	36	2.4	1.8	7	0.8	3.7
Spring disk	2421	399	36	2.1	1.9	8	0.4	2.7
Ridge-tillage	2414	357	36	2.3	1.8	5	0.7	2.7
No-tillage	2482	371	37	2.2	1.9	6	2.0	2.4
LSD _(0.1)	NS	43	NS	NS	NS	1	1.6	NS

^a Ex-Ca: ammonium acetate exchangeable calcium; Ex-K: ammonium acetate exchangeable potassium; Ex-Na: ammonium acetate exchangeable sodium; S: hot water extractable sulfur; TN: total Kjeldahl nitrogen; NO₃-N: nitrate nitrogen; NH₄-N: ammonium nitrogen; POM-C: particulate organic matter carbon.

^b NS: indicates no statistical significance among mean values at $P \leq 0.1$.

included in this long-term assessment of tillage and cropping systems because previous on-farm studies with similar soils (Karlen et al., 2002) had indicated K saturation was often less than the 20–50 g kg⁻¹ suggested by those favoring use of the basic cation saturation ratio (BCSR) concept (Eckert, 1987) for developing fertilizer recommendations for Midwestern soils. Furthermore, other long-term Midwestern studies (e.g. Barak et al., 1997; Liu et al., 1997; Russell et al., 2006) have shown significant effects on

CEC and base saturation due to ammonia-based N fertilizer applications, which for 1976 through 2006 totaled 5022 and 2956 kg ha⁻¹ for the CC and C/S fields, respectively.

Among the five tillage systems (Table 5) CEC was significantly lower within the 5–15-cm depth increment in both the CC and C/S fields after long-term moldboard plowing and for the 0–5-cm increment in the C/S field. Also, except for the 0–5-cm depth increment in the spring disk and no-till treatments, K saturation in

Table 8

Soil series effects on additional mean soil quality indicator values for the 0–5- and 5–15-cm depth increments in soils derived from glacial till 26 years of continuous corn (CC) or 31 years of a corn-soybean (C/S) rotation in central Iowa.

Texture group	Ex-Ca ^a (mg kg ⁻¹)	Ex-Mg (mg kg ⁻¹)	Ex-Na (mg kg ⁻¹)	S (mg kg ⁻¹)	TN (mg kg ⁻¹)	NO ₃ -N (mg kg ⁻¹)	NH ₄ -N (mg kg ⁻¹)	POM-C (mg g ⁻¹)
CC: 0–5 cm depth								
Loam	2608	358	32	1.9	2.0	12	1.3	5.8
Clay loam	2744	413	32	2.3	2.2	16	3.1	6.6
LSD _(0.1)	NS ^b	30	NS	0.4	0.1	2	NS	NS
CC: 5–15 cm depth								
Loam	2409	338	33	1.7	1.7	7	0.7	2.3
Clay loam	2717	407	34	2.3	1.9	7	2.0	2.4
LSD _(0.1)	172	27	NS	0.5	0.1	NS	1.2	NS
C/S: 0–5 cm depth								
Loam	2263	338	34	2.4	1.8	10	0.7	5.0
Clay loam	2654	452	36	2.6	2.2	12	1.5	5.9
LSD _(0.1)	186	31	1	NS	0.1	2	0.5	0.8
C/S: 5–15 cm depth								
Loam	2082	306	34	2.2	1.6	6.2	0.8	2.5
Clay loam	2610	407	37	2.4	2.0	6.5	1.2	3.4
LSD _(0.1)	156	28	1	NS	0.1	0.7	NS	NS

^a Ex-Ca: ammonium acetate exchangeable calcium; Ex-K: ammonium acetate exchangeable potassium; Ex-Na: ammonium acetate exchangeable sodium; S: hot water extractable sulfur; TN: total Kjeldahl nitrogen; NO₃-N: nitrate nitrogen; NH₄-N: ammonium nitrogen; POM-C: particulate organic matter carbon.

^b NS: indicates no statistical significance among mean values at $P \leq 0.1$.

the CC field was less than the suggested BCSR level of 20–50 g kg⁻¹. Comparisons between soil texture groups (Table 6) show significantly lower CEC values for the loam sites than for clay loam sites for both sampling depths following either a long-term CC or C/S rotation. Again, except for the loam 0–5-cm mean under CC, K saturation was below 20 g kg⁻¹. Low K saturation was especially evident within the 5–15-cm depth increment, and was one reason that supplemental studies focused on soil-test K were initiated at this site (Kovar et al., 2009). Presumably the very high Ca and Mg levels (Tables 5 and 6), which are characteristic of glacial till derived soils within the land form known as the Des Moines lobe (Prior, 1991), further aggravated the low soil-test K levels and contributed to the plant K deficiencies noted by Kovar et al. (2009).

Tillage system and soil texture group differences for exchangeable Ca, Mg, and Na, extractable S, TN, NH₄-N, NO₃-N, and POM-C are presented in Tables 7 and 8. For several of these potential soil quality indicators, there were statistical differences among tillage systems and between texture groups, but the magnitude of those differences were small and are considered to be insignificant with regard to crop growth, development or yield. The most consistent difference among the five tillage systems was that TN in samples from both depth increments within moldboard plow plots were lower than for the other tillage systems. The POM-C levels were also lowest for the moldboard plow treatment within the 0–5-cm increment after long-term CC or C/S rotations. Those differences are consistent with those discussed for total organic carbon (Table 1) and presumably reflect the lower soil organic matter levels in moldboard plow treatments. Unfortunately, baseline soil organic matter data were not collected when the study was initiated in 1975, so it is not possible to discern if the lower TOC levels in the moldboard plow treatments are due to the long-term tillage or inherent differences. Between the two soil texture groups, exchangeable Ca and Mg were, as expected, significantly higher at clay loam sites than at the more sloping loam sites. Also, as expected, POM-C levels in the 0–5-cm depth increment were generally twice as high as in the 5 to 15-cm increment, again

reflecting stratification and a rapid decline in soil carbon as sampling depth increases.

4. Conclusions

This study confirmed our hypothesis that long-term moldboard plowing and its associated secondary tillage operations would have the most negative impact on several soil quality/health indicators, especially those associated with TOC or one of the carbon fractions. In addition to TOC, CEC, WSA, MBC, and PMN all had lower values and/or SMAF scores in samples representing both texture groups where moldboard plowing had been used for either CC or C/S production.

This study also confirmed that low K saturation was very likely a chemical soil quality problem and supports conclusions by Karlen et al. (2013) that additional K fertility research is needed on glacial-till derived soils. Overall, based on our SMAF analysis, soils at this site were found to be functioning at between 75 and 85% of their potential. We conclude that developing less aggressive tillage systems or cropping systems that require less tillage could significantly improve soil quality/health even for some of the most productive soils in the world.

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Appendix A. Appendix

See Tables A.1 and A.2

Table A.1

ANOVA results ($P > F$) for 23 potential soil quality indicators measured for the 0–5- and 5–15-cm depth increments in autumn 2005 after 26 years of continuous corn (CC) on glacial till soils in central Iowa.

Indicator	Tillage (T)	Texture	Replicate	T × Texture
0–5 cm				
Aggregate stability (WSA)	0.0002	0.0001	0.0757	0.1710
Bulk density (BD)	<0.0001	0.0010	0.8286	0.1837
pH	0.0090	0.1175	0.0313	0.0422
Electrical conductivity (EC)	0.0144	0.2382	0.0263	0.5542
Bray P	<0.0001	<0.0001	<0.0001	0.0532
NH ₄ OAc exchangeable K (Ex-K)	0.3580	0.0006	0.0016	0.8542
NH ₄ OAc exchangeable Ca (Ex-Ca)	0.8564	0.0100	0.0025	0.1559
NH ₄ OAc exchangeable Mg (Ex-Mg)	0.8094	<0.0001	0.0515	0.5040
NH ₄ OAc exchangeable Na (Ex-Na)	0.0451	0.0680	0.1183	0.2184
CEC	0.2693	<0.0001	0.0108	0.1429
Extractable S	0.3559	0.3072	0.6056	0.2311
Total N (TN)	0.0002	<0.0001	0.0085	0.2713
Nitrate N (NO ₃ -N)	0.0002	0.0813	0.2365	0.3165
Ammonium N (NH ₄ -N)	0.1395	0.1633	0.0372	0.3414
Total organic C (TOC)	0.0012	<0.0001	0.0096	0.4677
Microbial biomass C (MBC)	<0.0001	<0.0001	0.0236	0.0483
Potential mineralizable N (PMN)	<0.0001	<0.0001	0.3385	0.2106
Particulate organic matter (POM-C)	<0.0001	0.3082	0.7509	0.1955
Percent base saturation (BS)	0.2510	0.0180	0.0158	0.2629
Percent K	0.2720	0.3349	0.5425	0.1714
Percent Ca	0.2696	0.0036	0.0183	0.1266
Percent Mg	0.4359	0.4404	0.4146	0.1591
Percent H	0.2510	0.0180	0.0158	0.2629
5–15 cm				
Aggregate stability (WSA)	0.2561	<0.0001	0.0033	0.2688
Bulk density (BD)	0.5069	0.0567	0.2427	0.6334
pH	0.0234	0.6067	0.0143	0.9060

Table A.1 (Continued)

Indicator	Tillage (T)	Texture	Replicate	T × Texture
Electrical conductivity (EC)	0.7664	0.9545	0.0597	0.7321
Bray P	0.3187	0.0003	0.0008	0.4336
NH ₄ OAc exchangeable K (Ex-K)	0.5906	0.6637	<0.0001	0.7962
NH ₄ OAc exchangeable Ca (Ex-Ca)	0.8402	<0.0001	0.0009	0.7535
NH ₄ OAc exchangeable Mg (Ex-Mg)	0.9725	<0.0001	0.0011	0.3930
NH ₄ OAc exchangeable Na (Ex-Na)	0.8775	0.0025	0.0805	0.4909
CEC	0.2460	0.0004	0.0158	0.8977
Extractable S	0.2897	0.2290	0.8109	0.0490
Total N (TN)	0.9310	<0.0001	0.0043	0.8985
Nitrate N (NO ₃ -N)	0.0012	0.0674	0.5300	0.7375
Ammonium N (NH ₄ -N)	0.7070	0.2621	0.0275	0.2962
Total organic C (TOC)	0.6478	<0.0001	0.0169	0.8472
Microbial biomass C (MBC)	0.0418	<0.0001	0.0893	0.2043
Potential mineralizable N (PMN)	0.5407	0.4405	0.2092	0.1821
Particulate organic matter (POM-C)	0.1700	0.0646	0.0227	0.1362
Percent base saturation (BS)	0.0818	0.6182	0.0263	0.8603
Percent K	0.5873	0.0029	0.2299	0.4394
Percent Ca	0.1009	0.6789	0.0374	0.9192
Percent Mg	0.1034	0.3471	0.0842	0.5814
Percent H	0.0818	0.6182	0.0263	0.8603

Table A.2

ANOVA results ($Pr > F$) for 23 potential soil quality indicators measured for the 0–5- and 5–15-cm depth increments in autumn 2005 after 31 years of a corn-soybean (C/S) rotation on glacial till soils in central Iowa.

Indicator	Tillage (T)	Texture	Replicate	T × Texture
0–5 cm				
Aggregate stability (WSA)	0.0002	0.0001	0.0757	0.1710
Bulk density (BD)	<0.0001	0.0010	0.8286	0.1837
pH	0.0090	0.1175	0.0313	0.0422
Electrical conductivity (EC)	0.0144	0.2382	0.0263	0.5542
Bray P	<0.0001	<0.0001	<0.0001	0.0532
NH ₄ OAc exchangeable K (Ex-K)	0.3580	0.0006	0.0016	0.8542
NH ₄ OAc exchangeable Ca (Ex-Ca)	0.8564	0.0100	0.0025	0.1559
NH ₄ OAc exchangeable Mg (Ex-Mg)	0.8094	<0.0001	0.0515	0.5040
NH ₄ OAc exchangeable Na (Ex-Na)	0.0451	0.0680	0.1183	0.2184
CEC	0.2693	<0.0001	0.0108	0.1429
Extractable S	0.3559	0.3072	0.6056	0.2311
Total N (TN)	0.0002	<0.0001	0.0085	0.2713
Nitrate N (NO ₃ -N)	0.0002	0.0813	0.2365	0.3165
Ammonium N (NH ₄ -N)	0.1395	0.1633	0.0372	0.3414
Total organic C (TOC)	0.0012	<0.0001	0.0096	0.4677
Microbial biomass C (MBC)	<0.0001	<0.0001	0.0236	0.0483
Potential mineralizable N (PMN)	<0.0001	0.2350	0.3385	0.2106
Particulate organic matter (POM-C)	<0.0001	0.3082	0.7509	0.1955
Percent base saturation (BS)	0.2434	0.1759	0.0057	0.2629
Percent K	0.2720	0.3349	0.5425	0.1714
Percent Ca	0.2696	0.0036	0.0183	0.1266
Percent Mg	0.4359	0.4404	0.4146	0.1591
Percent H	0.2434	0.1759	0.0057	0.2629
5–15 cm				
Aggregate stability (WSA)	0.2561	<0.0001	0.0033	0.2688
Bulk density (BD)	0.5069	0.0567	0.2427	0.6334
pH	0.0234	0.6067	0.0143	0.9060
Electrical conductivity (EC)	0.7664	0.9545	0.0597	0.7321
Bray P	0.3187	0.0003	0.0008	0.4336
NH ₄ OAc exchangeable K (Ex-K)	0.5906	0.6637	<0.0001	0.7962
NH ₄ OAc exchangeable Ca (Ex-Ca)	0.8402	<0.0001	0.0009	0.7535
NH ₄ OAc exchangeable Mg (Ex-Mg)	0.9725	<0.0001	0.0011	0.3930
NH ₄ OAc exchangeable Na (Ex-Na)	0.8775	0.0025	0.0805	0.4909
CEC	0.2460	0.0004	0.0158	0.8977
Extractable S	0.2897	0.2290	0.8109	0.0490
Total N (TN)	0.9310	<0.0001	0.0043	0.8985
Nitrate N (NO ₃ -N)	0.0012	0.0674	0.5300	0.7375
Ammonium N (NH ₄ -N)	0.7070	0.2621	0.0275	0.2962
Total organic C (TOC)	0.6478	<0.0001	0.0169	0.8472
Microbial biomass C (MBC)	0.0418	<0.0001	0.0893	0.2043
Potential mineralizable N (PMN)	0.5407	0.4405	0.2092	0.1821
Particulate organic matter (POM-C)	0.1700	0.0646	0.0227	0.1362
Percent base saturation (BS)	0.0818	0.6182	0.0263	0.8603
Percent K	0.5873	0.0029	0.2299	0.4394
Percent Ca	0.1009	0.6789	0.0374	0.9192
Percent Mg	0.1034	0.3471	0.0842	0.5814
Percent H	0.0818	0.6182	0.0263	0.8603

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